INSTITUTE NOTES.

JANUARY 1940.

FORTHCOMING MEETINGS.

Thursday, 22nd February, 1940. At 5.30 p.m. at the Royal Society of Arts, John Adam Street, London, W.C.2. **"The Testing of Greases,"** by M. W. Webber. (Meeting of the Lubrication Group.)

April, 1940. **Annual General Meeting.**

Additional Meetings may be arranged during February and March.

ELECTION OF OFFICERS.

The Council has elected Professor A. W. NASH, M.Sc., M.I.Mech.E. to be President of the Institute for the Session 1940–1941.

The following have been elected Vice-Presidents of the Institute for the Session 1940–1941 :

ASHLEY CARTER, A.M.I.Mech.E.
C. DALLEY, M.I.E.E.
F. H. GARNER, Ph.D., M.Sc., F.I.C.
J. MCCONNELL SANDERS, F.I.C.
F. B. THOLE, D.Sc., F.I.C.

ELECTION FOR COUNCIL.

In accordance with the Articles of the Institute, the following members of Council retire at the next Annual General Meeting in April, but offer themselves for re-election : E. A. EVANS, W. E. GOODAY, C. A. P. SOUTHWELL, A. BEEBY THOMPSON and C. W. WOOD.

One new nomination has been received on behalf of J. A. ORIEL, M.A. (Manager, Shell Refineries, Ltd.).

The Council has decided that, in view of present circumstances, a postal ballot will not be held, and the names of the above six candidates will be submitted to the Annual General Meeting of the Members to fill six vacancies on the Council.

NEW MEMBERS.

The following elections have been made by the Council in accordance with the By-Laws, Section IV, Para 7.

Elections are subject to confirmation in accordance with the By-laws, Section IV, Pars. 9 and 10.

Fellows.

IVANOVSZKY, Leo	London.
LYTLE, John Ebert	New York.

Transfer to Fellow.

STIGAND, I. A.	London.

Members.

DUNN, Roland	Belfast.
DYSON, Leonard Anderson Leighton	Belfast.
FARTHING, Vernon Lambert	Liverpool.
HANCOCK, John	Ayrshire.
JAMES, John Edmund	Essex.

Associate Members.

IDYLL, Clifton Purvis	Trinidad.
PEACOCK, William George	Birmingham.

POMEROY, Ralph Gaisford	Johannesburg.
SMITH, C. Gordon	Liverpool.
WARBROOK, Reginald Harold	Dublin.

Transfer to Associate Member.

MOORE, Philip Harold	Surrey.
NISSAN, Alfred Hesket	Birmingham.

Student.

IJDENS, Rente Albert	Delft.

CANDIDATES FOR ADMISSION.

The following have applied for admission to the Institute or transfer to another grade of membership, and in accordance with the By-laws the proposals will not be considered until the lapse of at least one month subsequent to the issue of this *Journal*, during which any Fellow, Member or Associate Member may communicate by letter to the Secretary, for the confidential information of the Council, any particulars he may possess respecting the qualifications or suitability of any candidate.

The object of this information is to assist the Council in grading candidates according to the class of membership.

The names of the candidate's proposer and seconder are given in parentheses.

EVANS, Frederick Neville Stuart, Divisional Superintendent, c/o Trinidad Leaseholds Ltd., Central Goods Yard, Reading, Berks. (*J. F. F. McQueen ; W. B. Heaton.*)

HOLLOWAY, Gilbert Lloyd, Geologist (Anglo-Iranian Oil Co., Ltd.), 22, Hawthorne Road, Birmingham, 30. (*A. W. Nash ; C. E. Wood.*)

KHALILI, Jawad, Student, c/o Anglo-Iranian Oil Co., Ltd., P.O. Box 1, Chertsey Road, Sunbury-on-Thames, Middx. (*A. W. Nash ; C. E. Wood.*)

MARSHALL, John Macintosh, Director (*Valvoline Oil Co.*), 131, Banks Road, West Kirby, Cheshire. (*J. Smith ; N. W. Smith.*)

PARK, James Harris, Engineer (*Serck Radiators Ltd.*), 118, Fabian Crescent, Shirley, Birmingham. (*F. Hepworth ; J. Gray.*)

PHIPPS, Leonard Frederick, Fire Brigade Officer, Central Fire Station, Singapore. (*L. H. Cooper ; A. J. Brown.*)

ROTH, Francis, Engineer (*Harold Moore*), Nordstjernan Oljeraffinaderibygget, Nynashamn, Sweden. (*H. Moore ; E. Stokoe.*)

ARTHUR W. EASTLAKE,
Honorary Secretary.

DESPATCH OF JOURNALS.

Owing to the war and the requirements of Censorship examination, members, and particularly those living abroad, are advised that considerable delays may occur in the receipt of their monthly *Journal*.

Journals for members in the United Kingdom are posted about the last day of the month. *Journals* for members overseas may not leave England until two or three weeks later.

MEETING OF U.S.A. MEMBERS.

A very successful dinner-meeting of members of the Institute of Petroleum residing in the U.S.A. was held at the Stevens Hotel, Chicago, on Wednesday evening, November 15th. Dr. Gustav Egloff presided over an attendance of about 250 members and their guests. Guests of honour included T. A. Boyd, General Motors Research Corporation, E. W. Webb, president, and Thomas Midgley, vice-president of Ethyl Gasoline Corporation.

During the course of the evening, Dr. Graham Edgar, vice-president and director of research, Ethyl Gasoline Corporation, gave an

address on "The Manufacture and Use of Tetra-Ethyl Lead." Dr. Edgar predicted spectacular advances in automotive power, foreshadowed by experiments already carried out to determine the possibilities of increasing compression ratio under conditions in which the anti-knock value of the fuel is no longer the limiting factor. Supercharging, generally applied so far only to aircraft, opened up another field of opportunity for utilization of fuels of high anti-knock value by the automobile engine. Tests with an 8-cylinder supercharged engine showed that it delivered a maximum horse-power nearly twice that of the un-supercharged engine. Thus, with 10 or 12 octane numbers improvement in fuel, it was possible almost to double the horse-power by supercharging. Dr. Edgar stated that about 75 per cent. of all motor fuel sold in U.S.A. contained tetra-ethyl lead, and in the aviation field almost all gasoline of 80 octane or over contained tetra-ethyl lead.

Amazing progress, said Dr. Edgar, had been made and was being made in the petroleum industry in modifying the structure of petroleum hydrocarbons to produce gasoline of high anti-knock value. Cracking and reforming, both thermal and catalytic, coupled with isomerization, alkylation, polymerization, aromatization, etc. were developing rapidly and were increasing both yields and quality of motor fuel.

The dinner-meeting was the fifth annual function of this character which the members of the Institute of Petroleum have arranged in U.S.A. The meetings are held during the week of the annual A.P.I. meetings.

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	PAGE
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A. F. Craig & Co., Ltd.	vi
Charles Dabell & Co.	—
Foster Wheeler, Ltd.	—
W. J. Fraser & Co., Ltd.	xiii
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Hadfields, Ltd.	iii
Hayward-Tyler & Co., Ltd.	xiv
Institution of Petroleum	x, xii
International Paint & Compositions Co., Ltd.	v
Lane-Wells Co.	iv
Lummus Co.	viii
National Supply Corporation	vii
Oil Well Supply Co.	—
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CONTENTS.

	PAGE
The Static Friction of Lubricated Surfaces. A. Fogg, M.Sc., and S. A. Hunwicks, B.Sc.	1
Some Notes on Plunger Lift Operations. F. R. Wellings.	19
Physical Constants of Asphaltic Bitumens. Part I. R. N. J. Saal, W. Heukelom and P. C. Blokker	29
Obituary. Donald C. Barton	40
The Development of Petroleum Refining. Presidential Address by Prof. A. W. Nash, M.Sc.	41
Solubility of Cracked Residues in Some Solvents. J. Voskuil	57
The Catalytic Effect of Metals on the Ageing of Lubricating Oil for Diesel Engines. H. L. Matthijsen	72
Burning Test for Kerosine	91
Institute Luncheon	96
The Flow Properties of Bituminous Materials. A. R. Lee, B.Sc., Ph.D., A.R.C.S., D.I.C., J. B. Warren, B.Sc., Ph.D., A.R.C.S., D.I.C., A.Inst.P., and D. B. Waters, B.Sc., Assoc.M.Inst.C.E.	101
The Synthesis of Lubricating Oils by Condensation Reactions. Part I.—The Condensation of Chlorinated Paraffin Wax with Aromatic Hydrocarbons. W. R. Wiggins, Ph.D., T. G. Hunter, Ph.D., M.Inst.Pet., and A. W. Nash, M.Sc., F.Inst.Pet.	129
The Manufacture and Use of Tetra-Ethyl-Lead. G. Edgar	146
Trinidad Geological Conference	150
Obituary. F. G. Edmed. N. A. Anfilogoff. J. A. L. Henderson	152
The Dependence of Viscosity of Liquids on Constitution. A. H. Nissan, B.Sc., A.M.Inst.Pet., L. V. W. Clark, Ph.D., M.I.Mech.E., F.Inst.Pet., and A. W. Nash, M.Sc., M.I.Mech.E., F.Inst.Pet.	155
Institute Meeting	212
Obituary. Eugene Coste	223
The Synthesis of Lubricating Oils by Condensation Reactions. Part II.—The Engine Testing of Synthetic Lubricating Oils. W. R. Wiggins, Ph.D., T. G. Hunter, Ph.D., M.Inst.Pet., and A. W. Nash, M.Sc., F.Inst.Pet.	225
Simple Petroleum Tables for Use with Density Hydrometers. Verney Stott, M.A., F.Inst.P.	235
Physical Constants of Asphaltic Bitumens. Part II. R. N. J. Saal, K. Meinema and P. C. Blokker	246
Some Experiments on Seizure between Lubricated Hard Steel Balls. D. Clayton, B.Sc.	256
Hazards Associated with Butadiene and its Peroxides. D. A. Scott	272
The Analysis and Testing of Lubricating Greases. M. W. Webber	273
Institute Meeting	284
Octane Ratings of a Number of Pure Hydrocarbons and of Some of their Binary Mixtures. J. Smittenberg, H. Hoog, B. H. Moerbeek, M.Inst.Pet., and M. J. v.d. Zijden	294
Twenty-Sixth Annual Report of the Council	304
Annual General Meeting	325

PAGE

The Classification of Oil Shales and Cannel Coals. A. L. Down, Ph.D., A.R.C.S., D.I.C., and G. W. Himus, Ph.D., M.I.Chem.E., A.R.C.S. 329

Errors in Acid-Bottle Readings. G. H. Scott, B.Sc. 349

The Use of Bitumen Emulsion in Soil Stabilization. A. E. Lawrence, B.Sc., A.I.C. 357

Soil Mechanics in Foundation Engineering. R. L. James, B.Sc., A.M.Inst.C.E., A.M.I.Struct.E. 365

Obituary. Charles K. Francis. G. W. S. Gibson. R. J. Stringer. F. B. Lea 375

The Manufacture and Testing of Roofing-Felts and Damp-Courses. D. M. Wilson, M.C., B.Sc., A.I.C. 377

Studies on the Separation of Paraffin Waxes. Part I. Principles involved in the Fractional Melting of Wax. M. F. Sawyer, Ph.D., T. G. Hunter, D.Sc., and A. W. Nash, M.Sc. 390

Researches on Asphaltenes. Part I. F. J. Nellensteyn and J. P. Kuipers . 401

Evaluation of Rotary Drilling Lines. H. C. H. Darley, B.Sc. 407

Piston Deposits, Ring Sticking, Varnishing and Ring Clogging. W. A. Gruse and C. J. Livingstone 413

Studies on the Separation of Paraffin Waxes. Part II. Phase Relationships. M. F. Sawyer, Ph.D., T. G. Hunter, D.Sc., Ph.D., and A. W. Nash, M.Sc. . 430

The Hydrogenation of Petroleum Fractions, Employing a Large Percentage of Catalyst. H. I. Waterman and C. Van Vlodrop 452

Control of Drilling Mud in the Field. H. C. Darley, B.Sc. 457

Synthesis and Properties of Mono-Normal-Alkylbenzenes. Part I. Methods for the Alkylation of Benzene. G. Shen, M.Sc., T. Y. Ju, B.Sc., and C. E. Wood, M.Sc., A.I.C. 475

Obituary. Victor Henny 488

The Clement-Pigneguy Knock Indicator. D. M. Clement and P. G. Pigneguy . 489

Synthesis and Properties of Mono-Normal-Alkylbenzenes. Part II. Preparation and Properties of the Intermediate Ketones and Corresponding Hydrocarbons. T. Y. Ju, B.Sc., G. Shen, M.Sc., and C. E. Wood, M.Sc., A.I.C. 514

Obituary. Sir Robert A. Hadfield 532

Further Investigations of the Properties of Clay Suspensions. G. D. Hobson, Ph.D., D.I.C. 533

Author Index 565

Subject Index 568

PAGE
329
340
357
365
375
377
390
401
407
413
430
452
457
475
488
489
514
532
533
565
568

PROF. A. W. NASH, M.Sc.

PRESIDENT, 1939–1941.

[*Frontispiece.*

Vol. 26. No. 195. January 1940.

THE STATIC FRICTION OF LUBRICATED SURFACES *

By A. Fogg, M.Sc., and S. A. Hunwicks, B.Sc. (Eng.).

Introduction.

The primary object of carrying out this investigation was to obtain information on "boundary" friction and the "boundary lubricating" properties or "oiliness" of various substances.

The two chief properties of fluids which determine their lubricating value are viscosity and some other property, independent of viscosity, usually known as "oiliness." Under static conditions any effect due to viscosity must necessarily be absent, since, by definition, viscosity is that property of a fluid which determines the resistance of the relative sliding motion of adjacent layers. The only resistance to the commencement of motion, therefore, is that due to the attractive forces between the solid surfaces as modified by the layer of lubricant between them. The effectiveness of this layer, known as the boundary layer, in reducing the attractive forces becomes a measure of the boundary lubricating properties of the lubricant which must be closely associated with "oiliness."

By means, therefore, of measurements of the resistance to the commencement of motion, *i.e.*, the static friction, a direct measurement of a property associated with oiliness can be made.

The exact mechanism of the boundary layer when motion has begun—for instance, whether it is still due entirely to the attractive forces of the surfaces, or perhaps to bending of the molecules in the boundary layer—is not known, but there is no doubt that the value of the static friction has a direct bearing on the quality of a lubricant.

As a further object, it was hoped that, if the method of test proved successful, it would provide a reliable and simple means of making tests for boundary lubricating properties of oils on a more exact basis than has been possible heretofore.

At the present time the only satisfactory method of test for the quality of a lubricant is a prolonged test under working conditions which is generally fairly costly. In many applications it is known that viscosity is a factor of importance and a flat viscosity–temperature curve is desirable. In some cases chemical stability is important, but in practically all cases, in varying degrees, the property of oiliness plays a vital part.

It appears, therefore, that in order to assess the value of a substance as a lubricant, it is necessary to consider, at least, the following three factors :—

(1) Viscosity–temperature and possibly viscosity–pressure relationships.
(2) Chemical stability.
(3) Lubricating value under boundary conditions.

* Paper received 22nd June, 1939.

The present investigation deals only with the last of these, and it must be realized, therefore, that if, as a result of this investigation, a substance is found to have good "oiliness" properties, it does not necessarily follow that this substance is a good lubricant for all conditions.

Apparatus.

Probably the most familiar apparatus used in static friction measurements, and one which is in use in the commercial testing of lubricants, is the Deeley machine. This machine was designed many years ago for the study of "oiliness" characteristics and the variations in frictional resistance produced by different combinations of metallic surfaces. One of these machines was available when the present investigation was begun, and it was decided to explore its possibilities for the work. Many experiments had been carried out at the N.P.L. with this machine by different experimenters, but the machine had never been adopted as a regular testing machine because of the lack of consistency in results obtained under apparently identical conditions. For instance, with given surfaces, lubricant, and a fixed load, consecutive measurements of coefficient of friction have been found to vary by as much as 200 per cent. It is well known that an adsorbed boundary layer adheres strongly to a metal surface, and great difficulty is experienced in removing it. In the operation of the Deeley machine there has always been some uncertainty as to whether or not the adsorbed layers have been removed and the surfaces rendered clean before proceeding to another lubricant.

The arrangement of contact of the two opposing friction surfaces was also considered as a possible explanation of the inconsistency of the results obtained. The friction surfaces consist of three flat pegs, equally spaced on a circle on the underside of a carriage, resting on a disc. With this arrangement it is necessary, for similarity of contact of each of the pegs with the disc, that the flat bearing surfaces of the pegs all lie in one plane, a condition which can never be achieved exactly in practice. (It is not easy to see, however, why variations from the uniplanar condition should influence appreciably observations in the static boundary condition.)

As a result of these considerations, however, it was decided, firstly, to replace the three flat pegs by three balls, so that the condition of each contact should be the same and, because of the high intensity of loading at the contact areas of balls, the separating layer of lubricant should be reduced to the limiting molecular layer, and secondly, to endeavour to develop a technique of cleaning the surfaces which would at least ensure that a standard condition of cleanness is arrived at before a set of measurements is made with any lubricant.

A description of the apparatus with the above modification is as follows. It consists of the two opposing surfaces, one, a disc about 4 inches diameter, and the other, three $\frac{1}{2}$-inch-diameter balls equally spaced round a circle 3 inches diameter on the underside of a circular carriage. (The material used for the friction surfaces throughout this investigation was hard steel.)

The carriage engages with a torque measuring device consisting of a coiled spring with indicating mechanism. The pressure between the surfaces can be varied by loading the carriage with weights. The disc,

i.e., the lower friction surface, is carried in a bath which contains the lubricant under test, and a gas ring is provided under the bath for heating the oil, the temperature being measured by a thermocouple in the oil bath.

The machine is operated by slowly rotating the disc by means of an electric motor and gearing, the motor being mounted separately from the machine so as to reduce vibration to a minimum. The frictional resistance between the surfaces causes rotation of the carriage against the action of the spring, and the disc is rotated until slipping of the surfaces occurs, when a pawl-and-ratchet mechanism prevents the spring from unwinding. The torque produced by the spring on the carriage at slip is thus equal to the friction torque and, as the total load is known, the coefficient of friction is easily obtained.

Cleaning the Surfaces.

Most of the lack of agreement between the results of static friction measurements of various investigators can probably be attributed to failure to remove all traces of contamination from the metal surfaces before introducing another lubricant. The usual method adopted has been to use a solvent, and many such substances have been used with varying degrees of success. It appears, however, that this method is fundamentally unsound, and it is submitted that such a procedure can, at best, only result in the contaminating layers being replaced by an adsorbed layer of the solvent, or some of its more active constituents. Extremely volatile solvents might be expected to give the nearest approach to absolute cleanness, but, if the generally accepted conception of surface forces applies, it would appear that even with such solvents, attachment between surface molecules and solvent molecules would take place.

In view of these considerations it was decided to make a comparison of the static friction of hard steel surfaces when "cleaned" by various solvents or cleaning solutions, and when treated in such a manner that an actual layer of material was removed each time from the surfaces.

For this latter purpose it was decided to rub the friction surfaces with the finest grade of emery paper available "0000 blue back"—first removing surplus oil by means of trichlorethylene vapour—after the surfaces had been contaminated with various substances, and to determine the consistency of the results obtained after this treatment. The disc, *i.e.*, the lower friction surface, was rubbed on a sheet of the abrasive paper placed on a surface plate in order to maintain a flat surface. Measurements of the friction were made as quickly as possible after this treatment, and without handling the surfaces. In all, several hundreds of such observations were made, and the coefficient of friction was always between 0·56 and 0·60, with a mean value of 0·58. On a number of occasions the surfaces were left in the machine and, without contamination except from the atmosphere, the coefficient of friction, μ, measured at short intervals of time up to 1 hour. At the end of this period the value of μ was still above 0·50, showing a very slow rate of contamination.

The first solvent tried was trichlorethylene, both in liquid and vapour form; this substance is marketed commercially as a degreasing agent, and a vapour degreasing plant was used for the vapour-cleaning process. With liquid cleaning the value of μ was 0·33, and with vapour cleaning 0·45.

These values, and those following for other solvents, are the mean of several obtained after cleaning surfaces contaminated with a number of oils chosen at random.

The second solvent used was industrial alcohol (95 per cent.). The mean value of μ obtained was 0·43.

The cleaning process used by Hardy * in certain static friction measurements was then used. This process consisted of removing gross impurities by ordinary benzene or alcohol, rubbing the surfaces on a piece of wet felt sprinkled with chromium sesquioxide, rinsing under the tap to remove finer particles of chromium sesquioxide, drying with clean filter paper, and finally immersing in absolute alcohol just heated to boiling point; whilst still hot the surfaces were removed with clean tongs, rinsed twice with absolute alcohol and dried by draining. Before using this process the surfaces were covered with a light machine oil. After cleaning the mean value of μ was 0·49.

A further cleaning process used by Tomlinson † consisting of rubbing the surfaces, after the removal of surplus oil, with the finest quality cotton wool and a mixture consisting of 8 parts absolute alcohol, 2 parts ether, and 1 part ammonia was next used. The value of μ obtained was rather variable—a new position being used for each observation—ranging from 0·40 to 0·55, with a mean of 0·48.

None of these cleaning methods therefore appears to be as efficacious as the abrasive method. The latter may not, of course, produce a state of absolute cleanness; but since it gives a condition of higher and more consistent friction than any of the other methods, it is obviously a more desirable method to apply.

It might be argued that the abrasive method of cleaning produces a roughening of the surfaces, and thus gives a somewhat artificial value of μ. A number of further observations which were made on the above solvents appear to contradict this, and give further support to the submission that any solvent-cleaning method will leave an adsorbed layer on the surface. Having obtained a number of consistent values of μ of the order of 0·58 for the steel surfaces cleaned by the abrasive method, the above solvents, namely, trichlorethylene, alcohol, and the alcohol–ether–ammonia mixture, were each in turn placed on the clean surfaces, and the coefficient of friction measured. With liquid trichlorethylene the value of μ was 0·33, with alcohol it was 0·43, and with the alcohol–ether–ammonia mixture it was also 0·43; as compared with 0·33, 0·43, and 0·48 for each of these, respectively, when used as cleaning solvents.

In other words, the friction of the surfaces when flooded with the above substances is the same as when the surfaces are cleaned with these substances and the surplus is removed.

The amount of rubbing to produce the clean condition ($\mu = 0{\cdot}58$) was generally very small, except in those cases where there had been obvious chemical action between the lubricant and the surfaces.

An interesting experiment was made to determine the extent of contamination due merely to handling the surfaces after cleaning to the

* Lubrication Research, Technical Paper No. 1, 2nd Edition, Appendix, p. 52.

† "The Rusting of Steel Surfaces in Contact," G. A. Tomlinson, *Proc. Roy. Soc.*, **A**, Vol. 115, 1927.

"$\mu = 0{\cdot}58$ condition." The friction disc and the balls were lightly rubbed with the fingers, the hands being in a normal state of cleanliness and having had no contact with oil or grease since washing. The coefficient of friction, measured immediately afterwards, was 0·10. This result demonstrates the ease with which surfaces become contaminated and the enormous effect on the coefficient of friction. As will be seen later, the value of μ is of the same order as was obtained for animal and vegetable oils, and presumably the contamination resulted in an adsorbed layer of similar fat or oil from the human body. When an oil was applied to the clean surfaces, an additional precaution was taken against contamination from any other source. After the friction of the clean surfaces had been measured, they were rubbed with a mixture of emery and the oil to be tested, wiped with a piece of clean dry "Selvyt" to remove loose abrasive particles, and then finally immersed in the oil. This assured that the oil was present on the surface, available for adsorption as soon as the abrasion was finished.*

Effect of Size of Balls.

A number of observations were made at various loads with $\frac{1}{8}$-inch and $\frac{1}{4}$-inch-diameter steel balls using oleic acid as lubricant. Measurements of friction were made at temperatures up to 100° C. with both sets of balls, but there was no appreciable variation with either set at any of the loads or temperatures, the value of the coefficient of friction being in all cases between 0·08 and 0·09.

It was decided to adopt the $\frac{1}{4}$-inch-diameter size for all the work included in this report, but it is intended at a later stage to investigate the effect of curvature more fully.

Temperature and Load.

In all cases where it was safe to raise the temperature of the lubricant without danger of fire or explosion, observations of friction were made up to about 100° C. with temperature rising and falling.

With regard to load, preliminary observations were made with total loads on the carriage (including the weight of the carriage) ranging from 0·738 lb. to 5·904 lb., in order to determine the effect of variations in load. No appreciable variation with load over this range was obtained at any temperature; this independence of coefficient of friction with load is usually taken as evidence of complete boundary conditions. For all subsequent work the load was fixed at 3·690 lb., this being a convenient load for ease of operation of the machine.

The load of 3·690 lb. represents, according to Hertz's theory of elastic

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* A similar method was used by S. Livingston Smith and E. Glaister in experiments on the original form of Deeley machine. In these experiments the lower surface, which was a cast-iron disc, was prepared by washing in benzol and then spraying with hot water to remove all traces of oil. After drying it was lapped with flour carborundum and the oil to be used. (See "The Effect of Use on the Properties of Motor Oils," S. Livingston Smith and E. Glaister. The *Engineer*, 1st May, 1931, p. 476.)

deformation, a mean pressure between the balls and ring of 30·3 tons/sq. in. and a maximum pressure of 45·5 tons/sq. in.

Substances used for Lubricating the Surfaces.

The substances selected were, for the most part, recognized lubricants, but a number of common liquids were also included. A list of the substances used, divided into classes, is given below.

(1) Straight lubricating oils, ranging from fatty oils to highly refined mineral oils. At each end of this range oleic acid and B.P. paraffin were included, the former being typical of the active constituent of fatty oils and the latter as representative of the inactive constituent of mineral oils and the result of ultra-refining.
(2) Extreme-pressure lubricating oils.
(3) Graphited oil and compounded oil.
(4) Common liquids.

When the observations had been completed, no correlation was observable between viscosity characteristics and the friction results. The better known of the substances gave friction characteristics in an order similar to that generally accepted for the "oiliness" value of these substances, for example, all fatty oils were superior to all mineral oils, irrespective of viscosity.

A series of experiments was then carried out to determine the relationship between molecular weight and coefficient of friction. These results proved extremely interesting, and form the subject of a separate Paper.*

Results.

Fatty Oils.

The following vegetable and animal oils were chosen as being representative of the more common fatty oils in use :—

Vegetable Oils.—Castor, rape, olive, coconut.
Animal Oils.—Sperm, pale whale, neatsfoot, lard.

The friction of the steel surfaces when lubricated with each of these was measured at temperatures up to 100° C., the usual cleaning operation being performed at each change over.

Castor Oil.

The coefficient of friction (μ) varied only slightly with temperature, showing a tendency to rise as the temperature increased. At 20° C. $\mu = 0{\cdot}09_5$ and at 100° C. $\mu = 0{\cdot}10_5$. There was no appreciable difference with the temperature rising or falling, and thus no permanent change in the friction as a result of heating in air to 100° C.

* "A Note on the Mechanism of Boundary Lubrication suggested by the Static Friction of Esters," by A. Fogg, *Proc. Phys. Soc. Lond.*, 1940, Vol. 52.

Rape Oil.

There was no definite variation in friction with temperature, the mean value of μ being about $0{\cdot}10_5$. During the tests with this oil there was evidence of chemical action between the acid and the brass parts of the machine, indicated by a change in the colour of the oil to olive green, and a difference in colour of the brass oil bath above and below oil level.

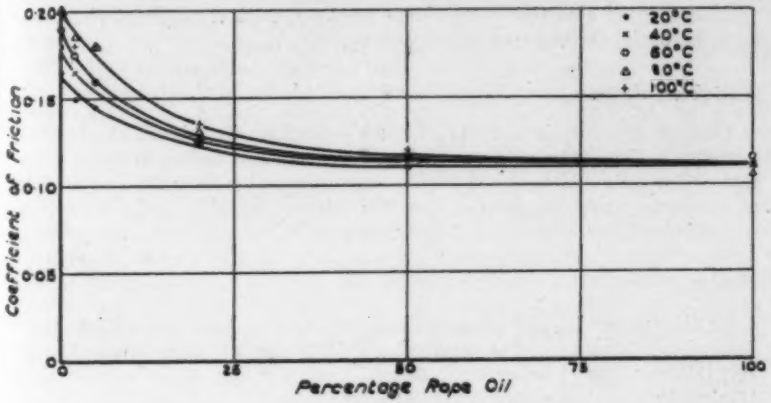

FIG. 1.

EFFECT OF ADDITIONS OF RAPE OIL TO MINERAL OIL.

Olive Oil.

The variation of friction with temperature was almost negligible, the mean value of μ over the temperature range 20–100° C. being $0{\cdot}10_8$.

Coconut Oil.

The coconut oil was a white, greasy solid at air temperature. A small quantity was melted and poured into the oil bath and over the friction surfaces. The oil was allowed to cool before making observations, the first test being made at 20° C., the oil then being solid. The mean value of four observations of coefficient of friction was 0·18, the carriage being moved to a fresh place each time. The temperature was then raised to 100° C. and the oil then allowed to cool, observations being made at intervals of approximately 20° C. From 40° C. to 100° C. and down again to 40° C., μ was very constant, its value being 0·08. It was necessary to wait overnight before the temperature had cooled to 20° C., and the first observation then gave $\mu = 0{\cdot}26$. Without moving to a fresh place, four observations immediately following all gave $\mu = 0{\cdot}08$. The high values at 20° C. are presumably due to the balls and ring becoming "welded" with solid fat; once this "weld" has been broken, the friction is low and independent of the physical state of the oil.

The boundary lubricating properties of this oil, therefore, appear to be the best of the vegetable oils tested.

Sperm Oil.

There was no variation of friction with temperature up to 100° C. either rising or falling, the value of μ being 0·10. There was therefore no effect on the friction as a result of heating in air.

Pale Whale Oil.

With this oil also the friction was very constant throughout the temperature cycle, the value of μ being $0{\cdot}09_5$.

Neatsfoot Oil.

There was a certain amount of solid separation in this oil at air temperature. The drum was warmed and shaken well before drawing off a sample for test. Although there was some separation from the test sample at air temperature, the results were not affected by this, and the friction was constant throughout the temperature cycle, the value of μ being $0{\cdot}09_5$.

Lard Oil.

Similar separation took place with this oil, and the same precautions were taken in drawing off a test sample. Again the results were unaffected by separation at air temperature, the friction was almost independent of temperature, and the mean value of μ was $0{\cdot}08_5$.

This group of oils may be taken as representative of all fatty oils, and it is interesting to note that the variation of friction, due to changes of oils within the group or to temperature, is quite small, the extreme values of the coefficient of friction being 0·08 and $0{\cdot}10_5$. A satisfactory feature of these measurements is that repetition was extremely good, and although mean values have been given, the departure of any one observation from the mean was small (about $\pm$ 0·01), being less than is usually encountered in friction measurements in any state except that of complete fluid film lubrication.

These two features, constant friction and consistency, are to be expected, since fatty oils are to a large extent composed of chemical compounds of similar constitution; the surfaces thus become covered with a layer which is, broadly speaking, homogeneous, and whatever relative position is taken up by the opposing surfaces the separating layer is always the same.

Straight Mineral Oils.

In order to cover briefly the normal range of viscosities of commercial straight mineral oils, the following three oils were chosen :—

Oil A—a light machine oil.
Oil B—a motor-car engine oil.
Oil C—a thick gear oil.

The above motor-car engine oil was a sample from a conventionally (acid) refined bulk supply, and a comparison was made with the same brand of oil (Oil D) refined by the solvent extraction process.

A synthetic oil, produced by the Fischer process at the Fuel Research Station, and the following commercial motor-car engine oils were also included, being samples remaining from supplies which had been submitted for other tests :—

Oil E } —extra light motor oils.
Oil F }
Oil G—a heavy motor oil.
Oil H—a medium motor oil.

Oil A. Light Machine Oil.

There was much more variation in the results obtained under constant conditions with this oil than with any of the fatty oils, and a change in friction with temperature.

The mean value of μ at 20° C. was 0·16, and at 100° C. 0·19, the increase being spread gradually over the whole temperature range.

Oil B. Motor-car Engine Oil.

This sample of oil was drawn from a supply refined by the conventional or acid process.

There was a gradual increase in the value of μ with temperature from 0·13 at 20° C. to 0·15 at 100° C., the friction falling to its original value when the oil was cooled to air temperature. Repetition of results was good at the lower temperatures, but there was a variation of about $\pm$ 0·02 in the value of μ at higher temperatures.

Oil C. Thick Gear Oil.

This oil was highly viscous, being in a "semi-solid" condition at air temperature.

The friction was almost identical with that of the previous oil, the value of μ ranging from $0{\cdot}12_5$ at 20° C. to 0·15 at 100° C. Repetition of results again was not so good as with fatty oils.

These results show that, for these three typical mineral oils, there is no definite relation between friction and viscosity. The increase in viscosity from the first to the second is accompanied by a reduction in friction, but the large increase in viscosity from the second to the third does not affect the friction.

To some extent, as viscosity increases molecular size increases and if, as is generally supposed, boundary friction is dependent on molecular length, then an increase in viscosity may, in some cases, cause a reduction in boundary friction. This would account for the reduction in friction as between the first two of these mineral oils.

Another point of interest in these measurements was the greater variation of friction between successive observations under the same conditions than was observed with the fatty oils. This may be due to the fact that mineral oils are composed of a large number of highly complex chemical compounds, some of which are probably adsorbed on different

parts of the surfaces; the friction will thus depend on the position of the contacts and whatever layer happens to be there.

Oil D. (*Solvent Refined.*)

The solvent extraction process results in improvements in viscosity–temperature characteristics and in chemical stability, but there appears to be some doubt as to its value when "oiliness" characteristics have to be considered. There is some reasonable foundation for this doubt, not so much from experimental evidence, but from the fact that solvent extraction is said to remove the more chemically unstable compounds, and it is these compounds, generally, which are the more "active" ones from a boundary lubrication point of view. The results of static friction tests indicate that the "oiliness" value is reduced by solvent extraction.

This particular sample of oil gave an increase in friction with temperature as with other mineral oils, but the value of μ ranged from 0·15 at 20° C. to 0·20 at 100° C. as against 0·13 and 0·15, respectively, for the corresponding conventionally refined oil; the results again were less consistent than with fatty oils.

It must be pointed out, however, that a definite case is not made out against solvent extraction by these results because of the lack of exact knowledge regarding the source and history of the two samples. Opportunity may be taken at this point of directing attention to the difficulty which is constantly arising in lubrication problems—namely, the lack of any means of identifying an oil and the absence of any suitable standards for comparison purposes.

A Synthetic Lubricating Oil.

This oil was produced by the Fischer process at the Fuel Research Station, but the quantity available was insufficient to fill the oil bath of the machine. The friction ring was covered, but it was impossible to make measurements except at air temperature. The friction was rather variable, as with mineral oils, and the value of μ varied between 0·12 and 0·16, with a mean of 0·14.

This result places the oil midway between the oils B and D, one conventionally refined, the other solvent refined. If judged by this test alone, therefore, this synthetic lubricating oil is up to the same standard of "oiliness" as normal motor oils.

Light Motor Oils.

The modern trend in lubrication of internal-combustion engines is towards oils of lower viscosity, the reasons being to decrease the time taken from starting to complete circulation of the oil and to reduce frictional losses in the engine. The latter will be achieved in those parts of an engine where fluid film conditions predominate, provided viscosity does not fall below some limiting value. During some parts of the piston travel, and possibly in other parts of the whole mechanism, however, boundary conditions probably exist, and the "oiliness" value of the lighter oils must therefore be taken into consideration.

Tests were made on oils E and F as being typical of the lighter oils in use.

Oil E.

The friction was almost unaffected by temperature up to 100° C., the mean value of μ over this temperature range being 0·19.

This oil was known to be solvent refined.

Oil F.

This oil behaved almost exactly as Oil E, the mean value of μ being 0·20.

Information regarding the refining process of this oil was not available.

The other two mineral oils tested gave results as follows :—

Oil G. Heavy Motor Oil.

The change of friction with temperature was small, the value of μ being $0{\cdot}19_5$ at 20° C. and $0{\cdot}20_5$ at 100° C.

Oil H. Medium Motor Oil.

There is some doubt about the composition of this oil; it is stated to contain certain inhibitors, and it may also contain a small amount of a vegetable oil. However, since it is used for the same purpose as others in this group, the results have been included here.

There was an increase in the value of μ with temperature from $0{\cdot}17_5$ at 20° C. to $0{\cdot}19_5$ at 100° C.

The results obtained for this group of oils show a fairly wide variation from $\mu = 0{\cdot}12_5$ to $0{\cdot}20_5$, a scale of values sufficiently open to allow the comparative boundary lubricating properties to be fairly easily assessed.

As one of the objects of the investigation was to examine the possibilities of this apparatus as a testing machine, it is obviously desirable that some standard substances should be available as references, and should preferably give results, at each end, at least, of a scale which is large enough to embrace all substances likely to be useful as lubricants.

As a step in this direction it was decided to make measurements with (1) oleic acid, for the lower end of the scale, and (2) B.P. paraffin for the upper end. The reasons for the choice of these two substances have been previously stated on page 6.

Oleic Acid.

The friction observations were very consistent, and independent of temperature, the value of μ under all conditions being 0·08.

This is lower than the value of μ for all other substances examined with the exception of coconut oil, which has the same value.

B.P. Paraffin.

This is not ideal for reference purposes, because it is not a single substance and its composition is unknown and may vary from time to time.

The results obtained were less consistent than with any of the substances so far used. A microscopic examination of the lower friction surface after tests to 100° C. indicated that very small pieces of metal had been torn

from the surface. This phenomenon repeated itself after the surfaces had been reconditioned. There was an increase in friction with temperature, and the mean value of μ ranged from 0·18 at 20° C. to 0·22 at 100° C.

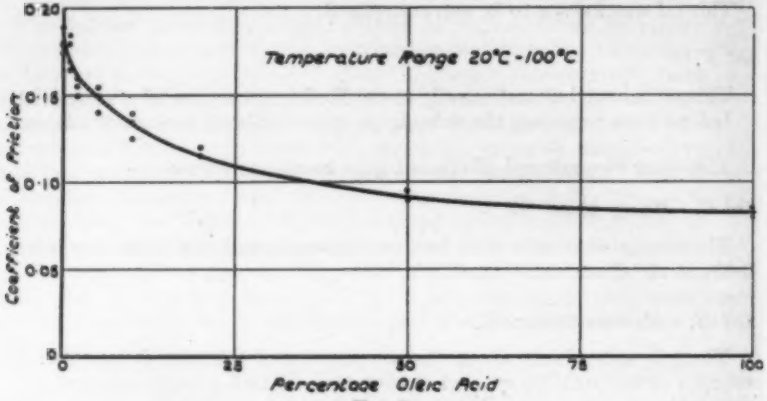

FIG. 2.

EFFECT OF ADDITIONS OF OLEIC ACID TO B.P. PARAFFIN.

These results give B.P. paraffin approximately the same boundary lubricating value as the poorer mineral oils; tearing of the surfaces, however, did not occur with any other of the mineral oils, and it is therefore difficult to understand why this should be exclusive to B.P. paraffin.

Extreme-pressure Lubricants.

The action of extreme-pressure lubricants is not clearly understood, but it is frequently stated that their action is not due to any superior "oiliness" qualities they may possess. Their ability to prevent seizure or breakdown under surprisingly high pressures is generally attributed to a chemical action between the "active" constituents of the lubricant and the metal surfaces, but the nature of the action is still the subject of some controversy.

In view of the controversial nature of the subject, it was considered desirable to measure the static boundary lubricating properties of a group of typical extreme-pressure oils in an attempt to provide additional information on the subject.

Friction measurements were made on each of the following :—

Oil J
Oil K
Oil L
Oil M
Oil N
Oil P
} Commercial E.P. Oils.

JXB oil (an oil obtained for reference purposes for extreme pressure measurements).

All these oils gave very consistent results, repetition being as good, if not better, than with fatty oils. Since the diluent or base oil is probably of mineral origin, and therefore a complex mixture of chemical substances, it appears that this part of the oil plays little or no part in determining the static friction, but that the whole of the surface is covered by the active constituents.

Oil J.

The friction was affected slightly by temperature, the value of μ being 0·11 at 20° C. and 0·12 at 100° C. On cooling, the friction passed through the same values as when the temperature was rising, μ being 0·11 at 20° C., thus showing no permanent effect on the oil by heating to 100° C.

Oil K.

The friction with this oil varied more with temperature, the value of μ rising gradually from 0·09 at 20° C. to $0{\cdot}11_5$ at 100° C. and falling again to its original value on cooling.

Oil L.

There was no variation of friction with temperature, the value of μ remaining at 0·09 from 20° C. to 100° C. with temperature rising and falling.

Oil M.

The friction was independent of temperature up to 100° C. and the value of μ was 0·10.

Oil N.

The friction decreased slightly with increase of temperature from 0·10 at 20° C. to $0{\cdot}08_5$ at 100° C., remaining at the latter value at all temperatures down to 20° C., when the oil was cooled.

Oil P.

The friction was independent of temperature up to 100° C., the value of μ being $0{\cdot}09_5$.

JXB Oil.

There was a small variation of friction with temperature from $0{\cdot}09_5$ at 20° C. to 0·11 at 100° C.

There is remarkably little variation between these oils as regards friction characteristics under static boundary conditions, and as a class they lie between fatty oils and straight mineral oils. They may be regarded, therefore, as having high boundary lubricating properties even up to 100° C., but this cannot be the reason for their extreme pressure properties, since fatty oils, which have higher boundary lubricating properties, have considerably lower extreme-pressure properties.

A short experiment was made to determine whether an extreme-pressure lubricant leaves a surface layer which is, in itself, an effective lubricant.

Clean surfaces were covered with Oil L and left standing overnight to allow ample time for any action which might take place. The following morning the surfaces were degreased in trichlorethylene vapour, which removed all visible oil. The coefficient of friction was then measured at 20° C., and was found to be 0·41, which is of the same order as was obtained by degreasing any contaminated surfaces with trichlorethylene. It appears, therefore, that if any action does take place between an extreme-pressure oil and a metal surface, resulting in a new surface layer, this layer has no separate influence on the friction.

Graphited Oil.

Graphite, in colloidal form, is widely recommended as an additive to mineral oils for the lubrication of many mechanisms. It is fairly obvious that under fluid-film conditions its presence can have no effect, except in so far as it may cause small changes in viscosity. It is, however, claimed that it forms on the metal surface a new surface known as a " graphoid " layer, and that this layer not only reduces the possibility of seizure should lubrication fail, but that it also causes a reduction in friction. This can only mean a reduction in friction under boundary conditions. Tests on the static friction machine would appear, therefore, to be a suitable means of verifying this.

Accordingly, the surfaces were cleaned and covered with Oil D (solvent refined) containing colloidal graphite. Friction measurements were begun immediately, and the first determination at 20° C. gave the same value of μ as for the untreated oil—namely, 0·15. As the temperature was raised, μ increased to 0·18 at 60° C., still behaving as the untreated oil. With further increase of temperature the friction began to fall, the value of μ at 100° C. being 0·16. The oil was then allowed to cool, and the friction gradually fell, the value of μ at 20° C. being $0{\cdot}12_5$, showing a substantial reduction on the value at the start of the temperature cycle. The machine was left untouched overnight, and next day friction measurements were made over the same temperature cycle. At 20° C. the value of μ was $0{\cdot}12_5$, rising to $0{\cdot}14_5$ at 100° C., and falling again to $0{\cdot}12_5$ at 20° C. A repeat of the whole of these measurements gave the same results.

It appears, therefore, that an appreciable reduction in friction is obtained by the addition of colloidal graphite to this mineral oil, the values of μ for the treated and untreated oil being, respectively, $0{\cdot}12_5$ to $0{\cdot}14_5$ and 0·15 to 0·20 over the temperature range 20° C. to 100° C. [The improvement obtained is approximately equal to the difference between the results for Oil B (conventionally refined) and Oil D (solvent refined).]

These results also show that the improvement is not immediate, and that an interval of time (or possibly an increase in temperature) is necessary for the changed conditions to be established.

In order to determine whether the graphited oil had any effect on the surfaces which would persist after removal of the oil, the surfaces were flushed well with benzene to remove all surplus oil.

Measurement of the friction then gave a value of μ of $0{\cdot}12_5$ at 20° C.—*i.e.*, removal of the surplus oil did not affect the friction, indicating that graphite in some form had been left behind on the surfaces. [It is

improbable that an effective adsorbed layer of oil was left behind, which might account for low friction, because flushing of the surfaces with benzene when they were covered with untreated oil gave a considerably higher value of μ. See results for benzene given later.]

The surfaces were then covered again, with untreated oil, the value of μ being $0{\cdot}12_5$ at 20° C., which shows that after using graphited oil, the friction of the surfaces remains at the low value obtained with the graphited oil when untreated oil is used afterwards. No attempt was made to determine the duration of this effect.

Compounded Oil.

Rape oil, in various proportions, is commonly used for compounding with mineral oils in order to improve the "oiliness" qualities of the latter. Generally, comparatively small proportions, of the order of 5 per cent., of rape oil are added, and it is generally thought that little, if any, further improvement would be obtained by exceeding this amount. In order to check this belief and the general effect of compounding, observations were made on mixtures of varying proportions of rape oil and the solvent-refined mineral oil, Oil D. The latter was chosen as being representative of the "inactive" or "non-polar" substances, and one, therefore, which would be expected to show the greatest improvement by compounding.

Mixtures containing 2, 5, 20, and 50 per cent. (by weight) of rape oil were made up, and friction measurements obtained up to 100° C. The results are shown in Fig. 1, coefficient of friction being plotted against percentage of rape oil in the mixture. It will be seen that the friction falls fairly rapidly, at all temperatures, with comparatively small additions of rape oil, but the friction at 100 per cent. (rape oil only) is less than for any mixture, the fall in friction being gradual from pure mineral oil to pure rape oil. For practical purposes, however, there appears to be little advantage in increasing beyond 20 per cent. rape oil, approximately three-quarters of the total possible gain being obtained at this mixture strength.

Experiments with another series of mixtures gave similar results. These were mixtures of oleic acid and B.P. paraffin, with amounts of the former of 1, 2, 5, 10, 20, and 50 per cent. (by weight). As mentioned earlier, these two substances are at the extremes of the "scale of oiliness" of the usual lubricating oils, and are therefore particularly suitable for observing the effects of compounding.

The results are shown in Fig. 2, coefficient of friction being plotted against percentage of oleic acid. This curve is similar to the one obtained for rape oil and mineral oil mixtures, the friction falling gradually from pure B.P. paraffin to pure oleic acid, the value of the friction for the latter being lower than for any mixture. The rate of fall of friction at small percentages of the "active" substance, however, was greater than in the previous case.

These results show, therefore, that a considerable gain in the boundary lubricating properties of a mineral oil is obtained by compounding with a fatty oil or a fatty acid, but that in neither case does the friction reach its lowest value before the percentage of the active constituent reaches 100 per cent., which is contrary to general supposition.

Common Liquids.

The substances included in this section are a few common liquids, generally assumed to have no lubricating value. They include some of the solvents previously mentioned as cleaning agents, namely, trichlorethylene, alcohol, and benzene; in addition, water, as being the most common liquid, and glycerin, a liquid with an "oily" appearance, were included.

Trichlorethylene.

This substance was frequently used during the investigation as a solvent for removing surplus oil, and a number of observations were made at different times of its effect on the friction. The results were very consistent, the mean value of μ at 20° C. being 0·33. With the vapour only coming into contact with the surfaces μ varied between 0·41 and 0·45.

Benzene.

This liquid gave the highest friction of all those used in this investigation, the mean value of μ at 20° C. being 0·48; the results were rather variable.

Alcohol.

The mean value of μ at 20° C. was 0·43; the variation from the mean was $\pm$ 0·02.

Distilled Water.

The results were very widely scattered, the value of μ ranging from 0·20 to 0·40 over the temperature range 20° C. to 60° C. At this stage, owing to the wide scatter, it was decided to examine the surfaces. They were found to be covered with rust and excessively corroded and, as the results were probably meaningless, the tests were discontinued. The rust was removed using various grades of emery paper, and the surfaces were then cleaned in the usual way before proceeding with tests.

Glycerin.

The friction showed a small increase with increase of temperature, but repetition at any one temperature was good. The value of μ increased from 0·20 at 20° C. to 0·25 at 100° C., and decreased to 0·20 at 20° C. when the surfaces cooled.

These results show that glycerin has slightly less boundary lubricating value than the poorest of the mineral oils tested.

The static boundary lubricating properties at 20° C. of all the substances used in this investigation are summarized in Fig. 3, where they are tabulated in the form of a scale. The coefficient of friction of clean steel on steel is shown as corresponding to minimum "oiliness," *i.e.*, the highest possible friction, whilst maximum "oiliness," as revealed by this investigation, corresponds with the coefficient of friction of oleic acid.

It appears from this diagram that a suitable scale of "oiliness" for those substances generally considered to be lubricants would have as its extremities coefficients of friction of 0·20 and 0·08.

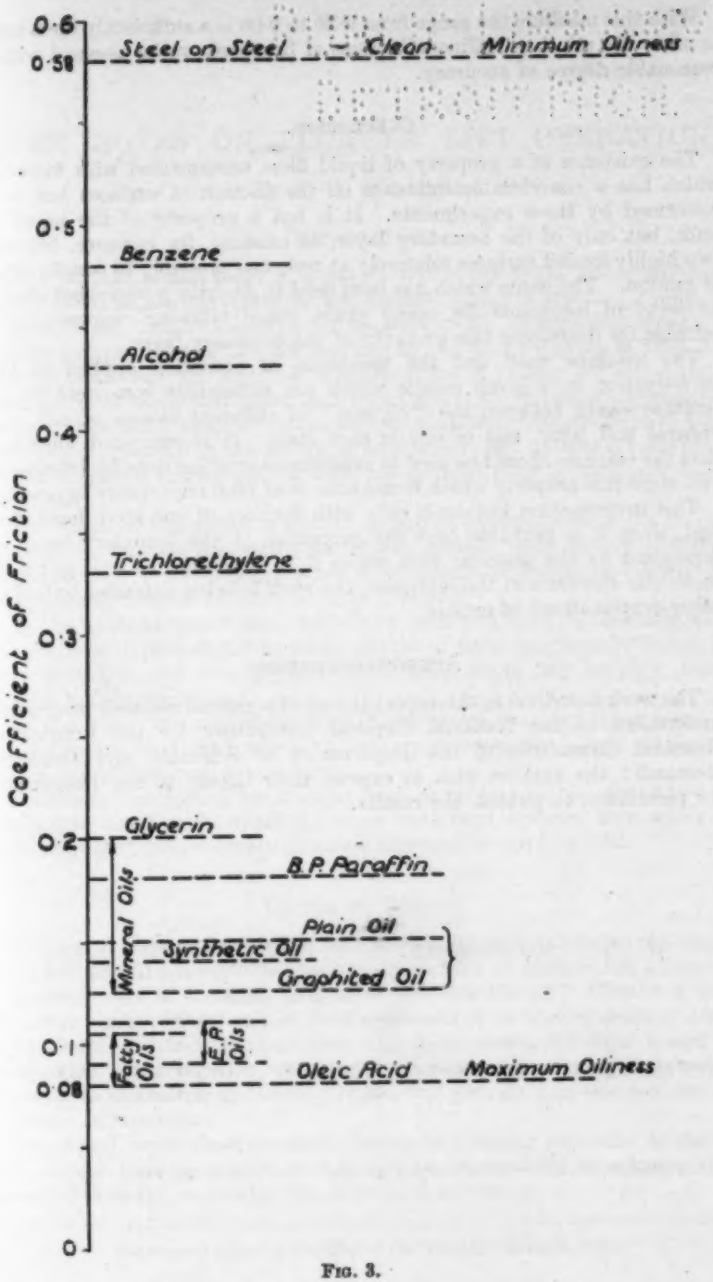

FIG. 3.

SCALE OF OILINESS AT 20° C. (STEEL SURFACES).

With this machine the range from 0·20 to 0·08 is a sufficiently open scale to allow the relative "oiliness" values of lubricants to be assessed with a reasonable degree of accuracy.

Conclusion.

The existence of a property of liquid films unconnected with viscosity which has a considerable influence on the friction of surfaces has been confirmed by these experiments. It is not a property of the liquid in bulk, but only of the boundary layer, as existing, for instance, between two highly loaded surfaces relatively at rest, and probably in certain types of motion. The name which has been used to describe a somewhat elusive property of lubricants for many years, viz. "oiliness," appears to be suitable for describing this property of the boundary layer.

The machine used and the technique of operation applied in this investigation have given results which are sufficiently consistent to distinguish easily between the "oiliness" of different classes of oils, *e.g.*, mineral and fatty, and of oils in each class. It is suggested, therefore, that the machine should be used to supplement existing tests for lubricating oils, since this property which it measures is of vital importance in practice.

This investigation has dealt only with surfaces of one kind, hard steel, and, since it is probable that the properties of the boundary layer are dependent on the material with which it is in contact as well as on the molecular structure of the lubricant, the work is being extended to include other combinations of metals.

Acknowledgements.

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SOME NOTES ON PLUNGER LIFT OPERATION.*

By F. R. Wellings.

Introduction.

The purpose of this paper is to put forward a few of the major problems encountered in the operation of the method of oil production known as "plunger lift," and to offer some suggestions for overcoming them. A previous paper, read before this meeting by Mr. G. A. Walling in 1935, has already dealt with the economic considerations of plunger lift and given a description of equipment used, and these points are consequently omitted here. Since 1935, apart from one or two simplifications, there have been no essential changes in the design of equipment, but increased knowledge of the operation of plunger-lift wells has enabled their performance to be improved.

The scope of this paper is limited to actual experience of wells on one field only, but as the wells considered possess such widely differing characteristics, it is hoped that a few of the general principles laid down will be applicable to wells on other fields in Trinidad.

In the author's experience, wells have been produced successfully with oil gravities of from 0·868 to 0·945, depths of from less than 1000 feet to over 4000 feet and with productions of from 20 to 350 brl./day, using 2½-inch and 3-inch units.

In the main, the equipment used has been of standard design, unless otherwise specified, and where chokes are referred to, ¾-inch maximum orifice, adjustable ones are implied.

Although overlapping has been avoided as far as possible, one or two of the points raised in Mr. Walling's paper have been repeated here, where it is thought that more recently obtained information can be added.

Choice of Wells.

At present it seems impossible, with any degree of certainty, to say which wells will or will not prove to operate successfully on plunger lift, although indications can be obtained from their previous history. Usually a well is put on plunger lift when it is nearing the end of its flowing days, or after it has been gas lifted for some time. In either case a few days' record of production characteristics, obtained by hooking up a two-pen pressure recorder to the casing and tubing heads, will provide a certain amount of evidence of suitability.

In general, wells showing steady casing and tubing pressures or gentle and regular heading conditions will operate successfully on plunger lift, provided they are reasonably free from sand and water.

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* Paper read before a Meeting of the Trinidad Branch, 1939.

Wells with irregularly variable pressures, indicative of uneven flow of fluid into the hole or the presence of free water, are likely to be troublesome. The same applies to wells heading violently with big changes in casing pressure. This condition may be indicative of high critical back pressure and locking of oil in the formation.

Other things being equal, wells with a low fluid level are more likely to cause damage to plungers than those with a high one.

Wells making sand can be produced on plunger lift, but unless the percentage is small, it would seem that they are best left for some other method of production.

Apart from wearing the plunger excessively, sand can also cause it to stick up in the tubing or prevent the valve from falling off its seat at the top of the stroke. Sticking in the tubing can sometimes be overcome by choosing a plunger the diameter of which has already been reduced by wear, although it has been found in a few cases that a brand-new plunger will give an even better performance in a sandy well. As would be expected, the grain size of the sand seems to be a deciding factor.

With regard to sand jamming the valve, it was suggested in Mr. Walling's paper that cutting small grooves in the valve face would prevent it. The author has had no personal experience of this method, but has found that the trouble can be eliminated to a certain extent by having a suitable clearance between the valve stem and guide, in the cage. About $\frac{1}{32}$ inch on the valve diameter seems to give the best results. Greater clearances sometimes allow of the valve being forced on to its seat by the pressure of gas or oil underneath it while falling. Furthermore, valve stems with large clearances show a greater tendency to become distorted.

Water in a well, unless in the form of a homogeneous suspension or emulsion, can cause uneven stroking, probably due to varying proportions of oil and water entering the footpiece. In a well with a high fluid level, uneven stroking may be no great disadvantage, but in one with a low fluid level, a short stroke may result in a damaged plunger valve.

As an indication of what sort of results may be expected when putting wells on plunger lift, out of forty-five wells with which the author has come in contact during the last two years, twenty-two gave very little or no trouble at all, eleven operated successfully for a time until either sand, mud or water entering the hole, or the fluid level falling too low, rendered their further production by this form of lift, uneconomical. The remaining twelve proved unsuitable from the start, the causes of failure being classified as follows:—

Seven—excessive quantities of sand, mud or water.
Four—fluctuating flow of fluid into the hole and locking of oil in the sand.
One—low fluid level and high gas-oil ratio.

The number of failures is not truly representative of the effectiveness of using previous flowing and gas-lift records in deciding the suitability of wells for plunger lift. In some cases the indications were unfavourable, and had another method of production been readily available, plunger lift would not have been tried.

Running in and Testing Tubing.

The position at which the tubing footpiece is to be set can be estimated approximately from a consideration of previous gas-lift or flowing data. As a rule it is advisable to set on the high side, as it is usually rather difficult to get a plunger to operate with too low a tubing submergence. Once operation has begun, the correct submergence can be decided on. It need scarcely be said that the tubing should be set finally as low as possible consistent with steady operation.

Wells with tubing set to give an operating casing pressure of over 175 lb./sq. in. frequently give trouble through the fluid column being high enough for gas lifting to take place while the plunger is falling.

Wells with a casing pressure below 30 lb./sq. in. are often difficult to start up without damaging a plunger.

A point concerning the actual running of the tubing might be mentioned here. Plunger-lift tubing being manufactured to such fine limits, any slight distortion is sufficient to prevent the free fall of the plunger; hence it is essential to test each joint while running. A broach may be suitable for this, but it has been found that, in many instances, a broach will pass a tight spot where an unworn plunger will not. It is therefore advisable to lower a new plunger on a rope through each joint *after* screwing in. Any joints with tight spots or crooked threads should be rejected. Broaching, though useful in removing scale, etc., will seldom free a tight spot effectively.

The use of another set of elevators in place of slips is recommended while running in. With the latter there is always a tendency to squeeze the tubing, and when supporting several stands, the distortion, though not necessarily permanent, may be enough to prevent the test plunger from entering.

The bottom bumper should be inspected, before running in, for sand cutting directly underneath the mushroom head of the cushion seat; that is, assuming the footpiece has previously been in use.

Significance of Well-head Pressures.

Before considering the practical details of getting a plunger to function, it may be as well to emphasize the significance of the pressures at the casing and tubing heads. For noting these a 0–300 lb./sq. in. two-pen pressure recorder is most desirable, though indicating gauges are suitable.

When a well is in a condition of gas lifting, the fluid level in the casing will be at the tubing footpiece. Thus:—

Recorded casing pressure $\doteq$ Recorded tubing pressure + Head of fluid in the tubing + Friction pressure drop.

By closing the well for a few moments, eliminating friction pressure drop, the difference in casing and tubing pressures will indicate the head of fluid in the tubing.

It is not so important to know the actual height of the fluid column as to be able to tell whether there is any column there at all. This is usually possible even when the outlet choke is open.

Starting Up.

This operation calls for considerable care, as a plunger can receive more damage in its first few strokes than in several months of steady operation, particularly in wells with low fluid level and high gas–oil ratio. The usual procedure is as follows :—

After the tubing has been landed, the well is brought into a straight lifting condition either by swabbing or, if the fluid level is low enough, by applying gas. In cases where the tubing footpiece is set below the top of the perforations, the application of gas to the casing head may be rendered ineffective through the input gas entering the upper part of the sand. As soon as the well kicks off, the casing pressure begins to fall back, and the plunger can then be dropped, and, under certain conditions, will continue operating without further attention. Occasionally, if large quantities of fluid are being produced while the casing pressure is falling, the upward flow will hold the plunger up or will close the valve before the plunger reaches bottom, and cause it to return almost empty. Either trouble can usually be avoided by waiting until the casing pressure has fallen back more.

So long as oil is being produced while the plunger is dropping, this method is satisfactory, as there is sufficient differential between the formation and tubing footpiece to raise the plunger and oil slug to the surface when the flow is temporarily stopped, without forcing oil back into the sand. When the plunger falls back, the release of the gas in the tubing will allow enough oil to enter to reduce the plunger's speed before again hitting the cushion seat.

However, in wells in which conditions are such that efficient straight lifting will not take place, but where only gas or oily mist will reach the tubing head, the situation is very different. Provided a large quantity of formation gas is not being produced, the column of oil and gas in the tubing will be practically in equilibrium with the sand face pressure and the column of oil between the footpiece and the sand face. Hence, when the plunger reaches the footpiece, an increased pressure will be required underneath it in order to raise it again. This will be obtained by the applied gas or formation gas forcing the fluid level in the casing below the footpiece, causing oil to run back into the sand. As the plunger falls again, the pressure is released and the fluid level rises, but usually not fast enough to get to the footpiece before the plunger hits the cushion seat, travelling at a high velocity. One such impact as this may be sufficient to bend or upset the valve enough to prevent its functioning. Furthermore, on the return trip the empty plunger will damage the rubber bumper at the surface, unless the outlet choke is throttled immediately.

This trouble can be avoided if the plunger is trapped in the stack after the first trip, and the tubing pressure allowed to blow down until the oil level has risen again. While the tubing pressure is bleeding off, the two recorder pens will mark out almost parallel lines on the chart, until oil starts to enter the tubing, at which point the tubing pen will commence to move more quickly towards zero. As soon as this change in direction is noticeable, the plunger should be released.

The method the author has found to give the best results in nearly all cases is the following.

Any time after the well is brought into a straight lifting condition both inlet and outlet chokes are closed in, allowing the oil to fall back to form a column in the tubing. When this is done, if both tubing and casing pressures are the same, all the oil will have been forced down below the footpiece, in which case the outlet choke is opened slightly and gas bled off until the oil has once more returned. Except in wells with a high formational gas–oil ratio or low fluid level this is seldom necessary.

The plunger is released, both chokes being kept closed until bottom is reached. The outlet choke is then given a suitable opening, and the release in pressure allows the plunger to rise and deliver its load. At no time during the procedure has the casing pressure been raised sufficiently to force oil away from the footpiece, and so there is no fear of the plunger falling back in empty tubing.

The maximum tubing pressure reached during the first head can be used as an indication of approximate choke settings. If this pressure reaches to within about three-quarters of the casing pressure, the plunger will probably continue to operate on the original setting, for a time at any rate. If it reaches to within less than half, input gas should be applied, or the outlet choke throttled immediately the plunger starts to fall back.

In low-fluid-level wells this method of starting is particularly useful, as with a small slug of oil it is not always possible to trap the plunger after the first stroke. Even with the main-flow arm closed and the bypass open, the retarding force on the rapidly moving plunger is sufficiently great to push the valve off its seat, allowing the plunger to fall back too soon.

Setting of Chokes.

From what has been said under a previous heading, it will be seen that the size of the slug of oil delivered by the plunger on each trip will depend on the difference between the tubing and casing pressures at the moment the plunger touches bottom. A small opening on the outlet choke will allow the gas to escape slowly while the plunger is falling, and the pressure will therefore be fairly high at the moment of impact, and the head of oil correspondingly small. A large choke opening will give the opposite effect. A large enough opening to allow the tubing pressure to fall almost to zero before the moment of impact will obviously be undesirable, as the fluid level in the casing will have to be forced below the footpiece in order for the column to be lifted. On the other hand, too small a choke opening will not allow sufficient oil to enter the tubing. Furthermore, the upward velocity of the plunger may be so reduced that gas will bypass it and allow it to fall back.

The correct pressure at impact—somewhere between these extremes—will be different for each well, but in general it is found that best results are obtained when it is such that the pressure of the gas above the oil slug will fall to zero just before the top of the slug reaches the outlet choke. In other words, the curves on the recorder chart for each head should have a fairly sharp point touching the zero line. If a gas separator is used, the points will touch the separator pressure line.

Some wells can function steadily with flat-bottomed curves (indicative of tubing pressure being low at the moment of impact), but frequently wells operating in this way have a tendency to produce alternate large and small heads.

With a well operating on formation gas alone, unless gas is bled from the casing, the shape of the curves will be decided by the setting of the outlet choke alone. If, however, gas is being applied to the casing, it will be seen that any change in the gas-choke opening will have the same effect on regulating the tubing pressure at the moment of impact as an opposite change in the outlet choke. It therefore follows that in order to reduce the input gas to a minimum, the outlet choke should be throttled in as much as possible

Since most plungers operate below the critical back pressure at which maximum production can be obtained, alterations of the outlet choke setting over quite a large range does not appreciably affect the quantity of oil produced. The limit of throttling is reached when :—

(*a*) The energy required to lift the plunger itself a greater number of times balances out the energy conserved by throttling.

(*b*) The time of discharge of the oil slug through the restricted opening takes up too large a portion of the time of each cycle.

The effect of the limiting factor (*b*) can be reduced to a minimum by the adoption of some form of "surge chamber." This consists of a chamber placed between the tubing outlet and the choke, of sufficient capacity to hold the greater part of each slug of oil. Its use was suggested in Mr. Walling's paper as a means of preventing B.S. from settling back into the plunger on the upward trip, but it has the further advantage that it will allow of oil passing through the choke while the plunger is falling, thus reducing the time taken during the cycle for the oil slug to be discharged from the tubing. With this arrangement the outlet and inlet chokes can be closed in still further without any decrease in production, but with a decrease in input gas. For example, on one well which the author has operated the installation of a choke box enabled the input gas to be reduced by about 30 per cent. and the oil production to be increased from 200 to 220 brl./day.

On wells with a high formational gas–oil ratio it may be necessary, for maximum production, to open the outlet choke as wide as possible, or even to remove it altogether. Another trouble may be experienced by doing this, however. The velocity of the plunger through the fluid at the bottom of the tubing will depend largely on the quantity of free gas present. A fluid containing a large quantity of free gas, approaching to the consistency of froth, may have insufficient retarding effect on the plunger, and the impact on the cushion seat will be heavy. A back pressure maintained on the tubing increases the "viscosity"—if that term may be used—of the gas–oil mixture, by reducing the gas volume. Although the author has never tried it, it seems reasonable to assume that bleeding gas from the casing could have the same effect as throttling in this particular form of trouble.

Treatment of Worn Plungers.

Plunger wear varies greatly from well to well. In some wells a few weeks' operation is sufficient to reduce the plunger diameter by as much as 0·080 inch, whereas in others, plungers have operated a matter of years with scarcely any appreciable wear. How much a plunger can wear before

requiring rebuilding or scrapping seems to be open to some doubt. In two particular instances, to the author's knowledge, plungers have operated when the rings have been worn completely off one side and the threads on the cage exposed. Generally about 0·080 inch reduction in diameter is considered to be the economic limit.

A plunger usually wears on a taper, the greatest diameter being across the top, and the least across the cage. If sand is present in the tubing, this taper seems to increase the tendency to stick up, by the wedging action on the sand. In one well with which the author has come in contact the sand conditions were such that new and very much worn plungers stuck in the tubing on the downward trip with equal regularity. A slightly worn plunger with the taper skimmed off in the lathe functioned perfectly satisfactorily.

In Mr. Walling's paper it was suggested that worn plunger barrels could be built up by the deposition of metal with a welding torch. Another method, which has been successful, consists of skimming off the worn rings completely and turning down the barrel to such a diameter that detachable rings, made of special abrasion-resisting steel, can be slipped on. These are held apart by spacers and kept in position with a locking ring, screwed and spot welded on the base of the barrel. After the initial lathe work the rings can be replaced speedily and easily when worn. The cages, of course, have to be built up with a torch.

Probably the commonest source of trouble encountered in plunger lift is the upsetting or bending of the valve stems. Heating, then straightening or forging down, is usually necessary, with suitable tempering afterwards. It is advisable in all cases to give a fairly fine lathe finish to a treated valve stem, since the slightest roughness seems to provide a "tooth" for sand to pack and jam the valve on its seat.

Valve guides receive a fair amount of wear. Fitting replaceable steel bushings has been found to be a satisfactory cure for this.

Two-Piece Plungers.

In an attempt to reduce the number of temporary shut downs through bending or upsetting of the valve-stems, a cageless, two-piece plunger was evolved. The lower part consisted of a reinforced valve, fitted with guides to maintain it in a vertical position, and the upper part was the plunger barrel, with its lower end machined to form a seat for the valve. The internal cross-sectional area was arranged so that the barrel should have a slightly lower falling velocity than the valve.

Satisfactory operation has been obtained with this plunger in one or two cases, for short periods. Due to the relatively small surface in contact with the tubing, however, wear on the valve guides was excessive.

Fishing a sanded-up plunger of this type is a longer job than fishing a standard plunger. Either the barrel has to be recovered first and then dropped back again to recover the valve, or two separate runs have to be made with different fishing tools.

A simpler type of two-piece plunger which has been in use in this island for some time employs a loose steel ball to act as a valve. This has also given satisfactory operation for short periods, and in two cases known to

the author wells have operated with a plunger of this type when sand conditions were too severe for a standard plunger to function at all. The chief drawback was the difficulty of maintaining the ball in a central position when the barrel landed on it. Even with a concave cushion seat, the flow of gas and oil continually forced the ball out of centre, to the detriment of the ball seat and the lower end of the barrel.

All things considered, it seems that at present the disadvantages of two-piece plungers outweigh the advantages, although it is hoped that a slight modification in the design of the lower component in the former type described will make it a practicable proposition.

Conclusion.

The author would like to express his thanks to the management of Apex (Trinidad) Oilfields, Ltd., for permission to present this paper, and to Mr. Fullerton for advice and criticism.

DISCUSSION.

Mr. Harris (Chairman) : In opening the paper for discussion, I take the opportunity of congratulating the author on the very lucid way in which he has put the problems before us. I am proposing that comments on the paper should be replied to by the author directly after the comments have been made by each speaker.

Mr. Walling : I should like, first of all, to congratulate the author on his very interesting paper. I would like to know what experience the author has had in "parachuting" plungers—that is, in reducing the falling velocity by means of an orifice in the centre of the plunger. When my company first started plunger lift, many wells turned up in which the plunger hit bottom hard, due to too little fluid. On the advice of the manufacturers of the equipment, we introduced the system of placing an orifice in the plunger, and found that falling velocity could be controlled by the size of the orifice. This completely reversed our ideas about the system. In a well 1800 feet deep, producing at the rate of 2 brl./day, with the plunger making three to four strokes an hour, the overall cost was equal to 17 c. per brl. We were not interested in the shape of the pressure curves we obtained, provided the well operated without damage to equipment.

With regard to plunger lift, I would like to know what the author considers as a failure. Was his statement based on the study of charts, or was it a complete failure that could not be operated by any manner of means?

There is no doubt that the introduction of parachuting made a big difference, as far as our experience goes in defining the limit to which we can go. We have thirty wells producing an average yield of 10 brl./day each at an economic cost. I should like to know the cost of production as far as the author's experience goes. It is a fundamental point as to the value of the system in producing oil.

Mr. Wellings : I am afraid my experience as far as parachuting goes is rather limited, as in this field we seldom come across wells that require it. In one well where it was tried the results were not encouraging, as the decreased velocity tended to cause the plunger to stick. In another case of a low-fluid-level well, bleeding gas from the casing overcame the difficulty of the plunger hitting bottom hard. As mentioned in the paper, the consistency of the fluid at the bottom of the tubing is of first importance, and as removal of gas from the casing can affect this, it would seem that use of standard type plungers could be extended to many wells of low fluid level merely by bleeding off gas. It apparently requires very little fluid of the consistency of dead oil to slow down the plunger above the foot-piece.

As to what I call a failure, in this field we consider a plunger-lift well a success so long as it does not require too frequent attention or too many replacements. In some sandy wells the plunger will seldom make two successive strokes without sticking up,

and in wells with an erratic flow of fluid into the hole a plunger may be hammered up after an hour's operation. There is usually very little doubt whether a plunger-lift well is an economical proposition or not.

As far as production costs go, I am afraid I have not any exact figures to hand at the moment.

MR. PATERSON: If you have a large-scale operation, some sort of organization is necessary for continuous working. In my experience, causes which affect the operation of plunger lift are accumulation of paraffin, crooked holes, wear of plunger, too much gas, too much back pressure on well head, in some cases muddy and sandy wells, sticking of valve due to bending of spindle, and shortage of fluid in the hole. We have all these problems to face, and it is very evident that staff cannot attend to these all the time. We have had to develop an organization of local operators. We cannot pay too much attention to chart characteristics.

We have classified wells into certain groups, according to the trouble they give. The plungers have to stand up to heavy usage, but there is a definite limit to parachuting, depending on sand, mud, etc. All our wells are economically produced. In cases of small producers, the charts show that they are sometimes one or two hours off production, but are automatically brought back. Occasionally we have had to attend to wells continuously for a week before we could get steady operation.

In the case of erratic influx into the hole, there is nothing to be done to get continuous operation. As the fluid comes into the hole, the heads become larger and larger and then die down again. We operate such wells with the maximum amount of gas all the time, controlling the plunger speed during the time there is no fluid in the hole by parachuting.

MR. WELLINGS: As the number of wells with which I come in contact is small, it is quite possible for one staff engineer to control them all with the assistance of only one native operator per tour. We do not look upon plunger lift as our main method of producing non-flowing wells, and any well that continues to be excessively troublesome is put on to some other means of production.

MR. CASTLE: Mr. Walling has mentioned the economic side of plunger lift. I should like to know what changes there are in gas-oil ratio and production when a well is changed over from gas lift to plunger lift. Also I should be interested to hear whether anybody in the meeting has had any experience with improvements in the types of fishing tools used for fishing plungers.

MR. WELLINGS: With regard to your first query, the changes in gas-oil ratio and production vary enormously from well to well, when changing over to plunger lift. There is nearly always an improvement in gas-oil ratio, as would be expected, since plunger lift can be considered as gas lift without slippage. If a well on gas lift has been producing below its critical back pressure, there will be very little or no change in production when put on plunger lift. We have known wells which would not produce a barrel a day on gas lift without excessive quantities of input gas, yet turned out to be quite large producers on plunger lift.

MR. PATERSON: I should like to hear some of the author's experience of paraffin wells.

MR. WELLINGS: Here again I am afraid my experience has been rather limited, as we get very little trouble from paraffin on this field in any wells. Paraffinous wells that have been put on plunger lift here have turned out to be wells with erratic influx of fluid characteristics, so that they have scarcely had a fair test. In the few cases met with, however, it was found that the paraffin gave no trouble so long as the plunger was operating continuously. If for any reason the plunger was taken out of the hole and the well allowed to straight lift for a day or so, a thin paraffin scale forming on the walls of the tubing would prevent the plunger from falling when dropped again.

MR. THOMAS: On page 19, concerning the suitability of wells for plunger lift operation, the author states that, in general, wells with a steady tubing and casing pressure are suitable for plunger lift. Would not wells with such characteristics operate equally well without a plunger?

On page 25 two cases are quoted where plungers continued to operate even when the rings had been worn off completely. Would not the wells have gone on producing if the plungers had been taken out altogether ?

MR. WELLINGS : Plunger lift is introduced near the end of a well's flowing days to increase the efficiency of production. As previously mentioned, there is usually quite a large increase in production when such a well is put on plunger lift.

In the cases quoted where plungers continued to operate in a very worn condition, neither well would flow unassisted, and only gave a small production when straight lifting. It seems that the turbulence caused by the plunger's rings is capable of maintaining a seal of considerable cross-sectional area.

MR. WALLING : I would like to know whether the author has studied the question of running plunger lift tubing on the completion of wells, thus avoiding the necessity of having to pull the original flow string.

MR. WELLINGS : The question has been studied. Cost is usually the deciding factor. Since plunger lift tubing is considerably more expensive than ordinary tubing, it is not economic to tie it up in a well that is likely to flow for any length of time. Furthermore, unless the tubing happens to be set at the correct depth at the start, the services of a pulling crew are required anyway.

MR. PATERSON : On page 19, the author states : "In general, wells showing steady casing and tubing pressures . . . will operate successfully on plunger lift, provided they are reasonably free from sand and water." I would like to know something about this, as I have a case of a well producing 64 brl. of oil and 240 brl. of water per day.

MR. WELLINGS : My experience has tended to show that wells producing anything above about 5 per cent. of water are likely to give trouble sooner or later, especially in the case of low fluid levels. This need not apply if the proportion of oil and water flowing into the hole remains constant. If the proportion varies, short stroking will result, but, as already stated, this need not cause trouble in a well with a high fluid level.

PHYSICAL CONSTANTS OF ASPHALTIC BITUMENS. PART I.*

By Dr. R. N. J. Saal, W. Heukelom and Dr. P. C. Blokker.

Summary.

This paper gives a survey of the following physical properties of asphaltic bitumens: specific gravity, coefficient of cubical expansion, specific heat, thermal conductivity, permeability to water vapour, surface tension and total surface energy.

The methods by which these properties have been determined are described in detail.

Introduction.

Although the well-known tabulated surveys of the physical properties of materials, such as the American International Critical Tables, the German Tables of Landolt-Börnstein, and the French Tables of Abraham-Sacerdote, contain numerous data from literature on the physical properties of the most widely differing materials and compounds, they give practically no information about asphaltic bitumens.

This is partly due to the large number of asphaltic bitumens obtainable. Thus, in addition to the wide range of products differing chiefly in consistency which may be obtained from a single source, the number of bitumens is considerably increased by the fact that the physical properties may differ according to the method of preparation and the source of the starting material.

A second cause is the fact that data concerning particular properties such as consistency (penetration, softening point, brittleness, ductility, viscosity at fairly high temperatures) and temperature susceptibility are of greater importance for road building (formerly almost the only outlet for bitumens) than information about the normal physical constants.

As asphaltic bitumens are now more and more used for various industrial purposes, a knowledge of the physical constants that are of value for their various applications has become increasingly important. This applies in particular to the bitumens used for electrical and thermal insulation purposes.

We thought it desirable, therefore, to extend our knowledge of the principal data collected by us in the course of years by making further investigations, and to publish the results obtained.

It may be observed that the physical constants in question are in general only slightly affected by the consistency and origin of the bitumen—in other words, they are characteristic of fairly large groups of bitumens. For this reason it is sufficient to discuss the physical properties of only a few bitumens belonging to different groups.

The following physical properties will be considered:

specific gravity,
coefficient of cubical expansion,
specific heat,

* Paper received 25th April, 1939.

thermal conductivity,
surface tension and
total surface energy,
permeability to water vapour.

The electrical properties will be dealt with in a second publication.

Specific Gravity.

The specific gravity of bitumens having a penetration at 25° C. greater than 5 was determined by means of a pyknometer, that of harder bitumens by means of a hydrostatic balance.

In the determination with the pyknometer, this was partly filled with bitumen and partly with water.

Before the determination was carried out, the bitumen was heated for half an hour in the pyknometer at about 100° C. above its softening point R. & B., in order to remove any occluded air.

The figures obtained in these determinations are given in Table I.

Table I.

Specific Gravity of Asphaltic Bitumens.

Asphaltic bitumen.	Specific gravity at 25° C.
Pen. 100 g./5 sec./25° C. = 300	1·01 ± 0·02
" " = 200	1·02 ± 0·02
" " = 100	1·02 ± 0·02
" " = 50	1·03 ± 0·02
" " = 25	1·04 ± 0·02
" " = 15	1·04 ± 0·02
" " = 10	1·05 ± 0·02
" " = 5	1·07 ± 0·03
" " =< 5	1·07 ± 0·03

The specific gravities of bitumens partly depend on the origin of the crude oil from which they have been prepared, but in general they lie between the limits indicated in Table I.

For the rest, the specific gravity is only dependent on the penetration, and is therefore practically the same for bitumens of the pitch type, the normal type, and the blown type of the same penetration.

However, bitumens prepared from cracked residues are generally of higher specific gravity; bitumens from heavily cracked residues, for instance, yielded the following values :—

Pen. 100 g./5 sec./25° C. = 100	1·13 ± 0·02
" " = 50	1·13 ± 0·02
" " = 25	1·13 ± 0·02
" " = 15	1·14 ± 0·02
" " = 5	1·15 ± 0·02
" " =< 5	1·16 ± 0·02

Coefficient of Cubical Expansion.

A knowledge of the cubical expansion especially at high temperatures, is necessary for the calculation of tank-capacity in the case of bitumen delivered hot in tank-cars, as well as for the selection of coating materials

for objects to be exposed to considerable temperature variation. In the case of pothead compounds, where shrinkage on cooling is an important factor, cubical expansion of asphaltic bitumens is also of value.

In the bitumen laboratory of the Rhenania-Ossag Mineralölwerke investigations were made as early as 1929 in order to determine the coefficients of expansion of various bitumens.[1]

For the measurements at low temperatures (15–50° C.) a pyknometer was used, which was partly filled with bitumen and partly with water.

The determinations at high temperatures (120–200° C.) were made with a Mohr balance. With this instrument a sinker is lowered into the bitumen and the upward pressure exerted on the sinker determined.

The measurements made with Mexican distilled bitumens (pen./25° C. = 23 to pen./25° C = 196) showed that the coefficient of expansion is practically constant in the temperature range concerned, and almost identical for all bitumens. The coefficient of expansion seems to increase somewhat with the hardness of the bitumen (Table II); for further particulars see [1].

TABLE II.

Coefficients of Cubical Expansion of Asphaltic Bitumens.

Straight-run bitumens.	Coefficient of cubical expansion (α) for the temperature range 15–200° C.
Pen. 100 g./5 sec./25° C. = 196	0·00060
" " = 65	0·00061
" " = 50	0·00061
" " = 45	0·00061
" " = 23	0·00062

As may be seen from the following survey, the values given in the literature are in fairly good agreement with those listed above :—

Bureau of Standards, Washington [2]	between 15° and 65° C. = 0·00063.
American Standards Association [3] (See also [4])	" 15° " 230° C. = 0·00068.
H. Rossbacher [5]	" 25° " 70° C. = 0·00058.
H. Mallison [6]	
H. Mallison, F. Jacobsohn, and K. Sarre [7]	" 15° " 60° C. = 0·00062.

SPECIFIC HEAT.

The apparatus illustrated in Fig. 1 was used for the determination of specific heat. It consists of two parts : a calorimeter, and a device which serves to bring the bitumen to a predetermined temperature and to drop it into the calorimeter. Tube *B* is completely surrounded by the vapours from a boiling liquid which is heated in space *A*. In the top of this tube hangs a bucket-like container (*C*) covered with a lid, and containing the bitumen (about 10 gm.), which is maintained at a constant temperature. The copper block *D* serves to conduct the heat rapidly from the vapour to the bitumen. The temperature is measured by means of a thermo-element. The calorimeter, consisting of a double-walled vessel provided with water circulation, is under this heating device. The calorimeter contains a copper block *F* (the size of which depends on the temperature range covered by the determination), having a hole in which the receiver

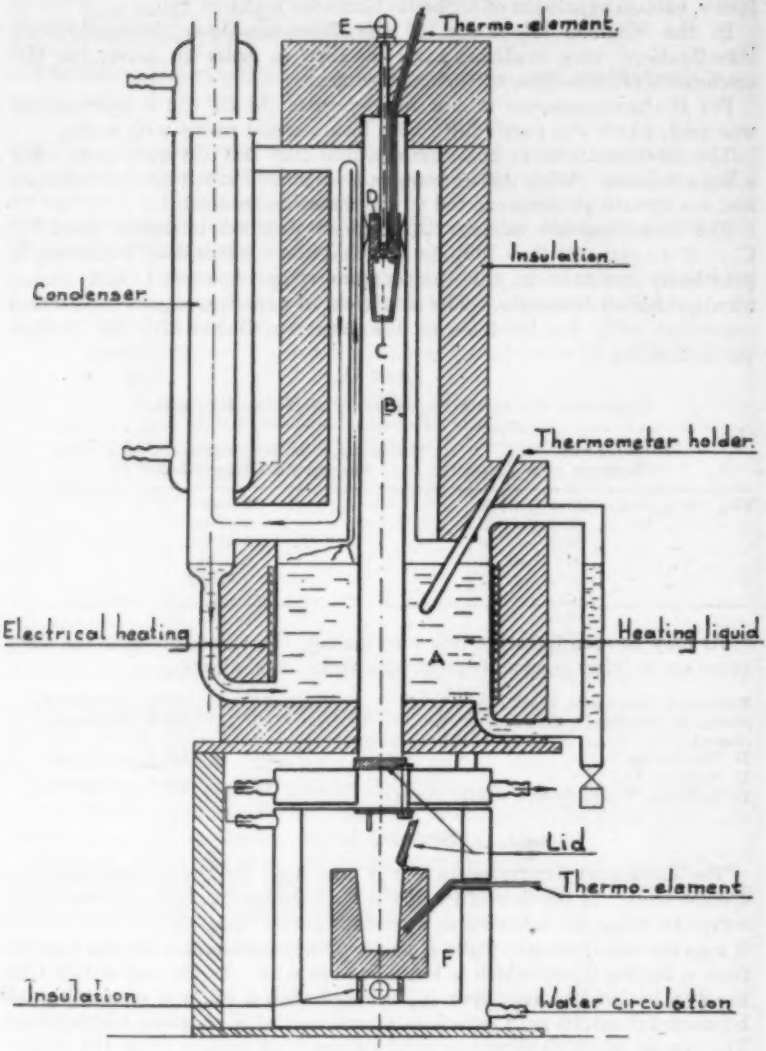

FIG. 1.

APPARATUS FOR DETERMINATION OF SPECIFIC HEAT OF ASPHALTIC BITUMEN.

(*C*) fits perfectly; this hole can be closed with a cover. By means of the rod *E* the bitumen container *C* can be loosened, so that it falls into the hole in the copper block; immediately afterwards both the cover of the copper block and the lid of the calorimeter opening are closed. Next, the rise in the temperature of the copper block *F* is measured with a thermo-element (and a mirror galvanometer) with an accuracy of $\pm$ 0·02° C. During the measurements both the water circulating in the calorimeter and the mirror galvanometer are maintained at a temperature of 25° C. $\pm$ 0·02° C. The temperatures to which the bitumen was heated were about 100, 200 and 300° C., respectively. Water, tetrahydronaphthalene and di-*sec.*-butyl-naphthalene, respectively, were used as heating liquids. The calorimeter was calibrated by means of a silver block of the same dimensions as the container *C*, weighing about 130 gm. The following values, calculated from the formula :—

$$c_p = 0{\cdot}055936 + 1{\cdot}05607 \cdot 10^{-3}\, t + 1{\cdot}86151 \cdot 10^{-6}\, t^2$$

were assumed for the specific heat of silver :—

0·05663	for the temperature range	between	100° C.	and	30° C.
0·05721	„	„	207° C.	„	30° C.
0·05785	„	„	322·4° C.	„	30° C.

(Landolt–Börnstein's Table.)

Before the determination, the copper block *F* was heated to a few degrees above 25° C. and the decrease in temperature measured over a small period of time. Next, the heated silver block was allowed to fall into the hole of the copper block as described above, and the further change in temperature was recorded. If the temperatures found are plotted against the time, it is possible to determine by extrapolation the temperature rise which would have occurred if no exchange of heat with the surroundings of the calorimeter had taken place. From the known heat capacity of the silver block, the heat capacity of the copper block could thus be determined. The specific heat calculated from these results is in good agreement with the values for copper given in the literature, as will be seen from the following table.

Temp. of silver block (Wt. 130 gm.).	Copper block No.	Weight copper block.	Heat capacity copper block in cal./° C.	Specific heat of copper.	
				Found (at ca. 30° C.).	Literature (Landolt-Börnstein's Tables).
100° C.	1	883 gm.	81·77–81·84	0·0927	
207° C.	2	1965 „	181·2–182·0–181·2–180·9	0·0923	0·09185 (25·8° C.) 0·09244 (38·1° C.)
322·4° C.	3	3432 „	316·7–319·4–318·2–319·1	0·0928	

The reproducibility of the results was about 0·5 per cent.

By means of the determined heat capacity of the copper blocks the specific heats of a number of bitumens were measured, taking into account the heat capacity of the container *C*, which almost corresponded to the heat capacity of the bitumen.

TABLE III.

Specific Heats of Asphaltic Bitumens.

Bitumen.	Pen./ 25° C. IPT.– A. 18.	Soft. pt. R. & B. IPT.– A. 20.	Specific heat in cal./gm./° C. at				Change of specific heat per 1° C. (a).
			0° C.	100° C.	200° C.	300° C.	
Venezuelan distilled bitumen . .	177	39½° C.	0·425	0·472	0·520	0·567	0·00047
Ditto . . .	23	62½	0·409	0·463	0·518	0·572	0·00054
Ditto . . .	7	96½	0·382	0·455	0·527	0·600	0·00073
Mexican distilled bitumen . .	22½	65	0·429	0·464	0·499	0·534	0·00035
Ditto blown bitumen . .	39	84½	0·430	0·462	0·494	0·526	0·00032
Ditto . . .	25	86½	0·402	0·458	0·514	0·570	0·00056
Bitumen from cracked residues .	2	73	0·419	0·459	0·499	0·538	0·00040
Light-coloured bitumen . . .	25	53	0·378	0·456	0·534	0·612	0·00078

The specific heat was determined in the temperature ranges of 100 to 30° C., 207 to 30° C. and 322 to 30° C. The figures obtained, calculated from the mean of three determinations, showed that the specific heat is a linear function of the temperature.

From this linear relation between specific heat and temperature, also at fairly low temperatures, it follows that a transition point, and consequently a definite melting point, does not occur.

The specific heats at convenient temperatures (see Table III) were calculated from the linear relation thus found, which may be indicated by the following equation :—

$$\text{specific heat} = \text{specific heat}_{0°C} + at \quad (t = \text{temp. in } ° \text{C.}).$$

If it is desired to measure the specific heat in the temperature range of t_1 to t_2, the average temperature t_m should be taken. Then the specific heat may be deduced from the values given in Table III with reference to the following equation :—

$$\text{specific heat}_{t_2-t_1} = \text{specific heat}_{0°C} + at_m.$$

According to the literature [2] the equation found for the specific heat of mineral oils :—

$$\text{specific heat} = \frac{1}{\sqrt{d}}(0{\cdot}388 + 0{\cdot}00081t)$$

(t = temp. in ° C.)
(d = spec. grav. at 15° C.)

may also be used for asphaltic bitumens (cf. also [3]).

However, our measurements show that in most cases the temperature coefficient of the specific heat is smaller than follows from the equation.

THERMAL CONDUCTIVITY.

To determine the thermal conductivity of asphaltic bitumens, the apparatus illustrated in Fig. 2 was used. This apparatus consists of a

spherical copper vessel A, in the middle of which is a solid copper sphere B, in which are two holes, one of which serves to contain the heating

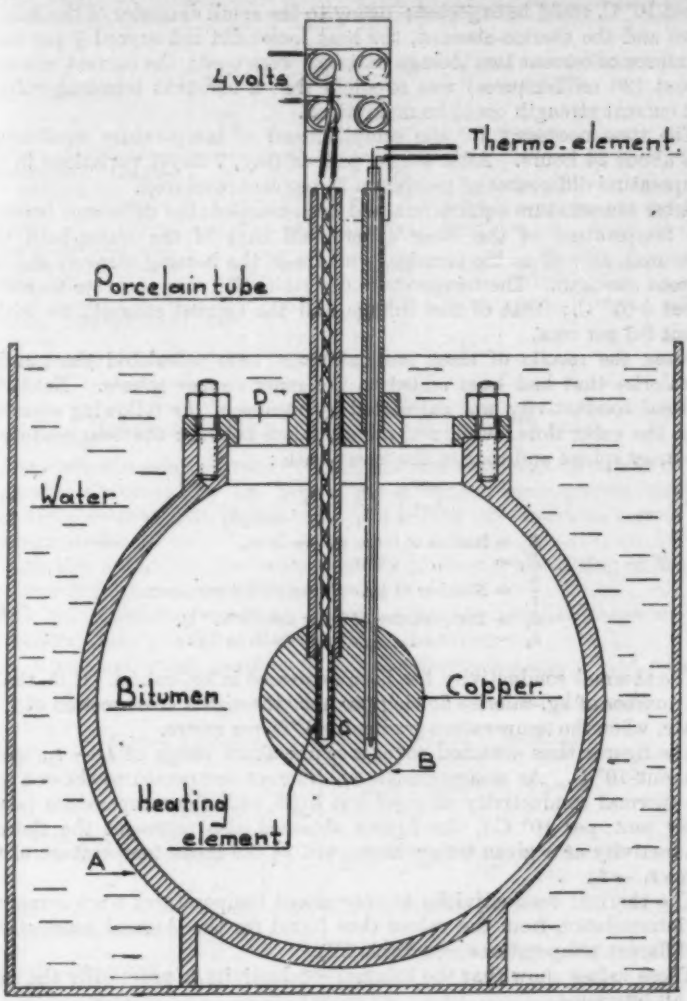

FIG. 2.

APPARATUS FOR DETERMINATION OF THERMAL CONDUCTIVITY OF ASPHALTIC BITUMENS.

element C, the other to contain the thermo-element. The space between the solid sphere and the wall of the larger sphere A was filled with bitumen, and the whole placed in a water-bath at constant temperature, so that water flows through the holes D into A and covers the bitumen.

The heating element was so adjusted that at a tension of 4 volts, and under conditions of temperature equilibrium, a temperature difference of about 10° C. could be expected; owing to the small diameter of the lead-in wires and the thermo-element, the heat losses did not exceed ½ per cent. As source of current two storage batteries were used; the current strength (about 130 milliamperes) was so slight that a constant terminal voltage and current strength could be maintained.

The time necessary for the establishment of temperature equilibrium was about 24 hours. After longer periods (say, 7 days) variations in the temperature differences of maximum 2½ per cent. occurred.

After temperature equilibrium had been reached, the difference between the temperature of the inner sphere and that of the water-bath was measured, as well as the terminal voltage of the heating element and the current strength. The temperature determination was accurate to within about 0·02° C.; that of the voltage and the current strength to within about 0·5 per cent.

From the results of these measurements were calculated the number of calories that had been added to the inner copper sphere. Next, the thermal conductivity was calculated by means of the following equation from the value thus found, and the difference between the temperature of the inner sphere and that of the water-bath:

$$\lambda = \frac{\phi}{i} \cdot \frac{R_2 - R_1}{\delta_1 - \delta_2} \cdot \frac{1}{4\pi R_1 R_2}.$$

R_1 = Radius of inner sphere in m.
R_2 = „ outer „ „
$\frac{\phi}{i}$ = Number of kg.-calories added per hour.
δ_1 = Temperature of inner sphere in ° C.
δ_2 = „ water-bath in ° C.

The thermal conductivity has been expressed in kg.-cal./m./°C./h, that is the number of kg.-calories flowing per hour through a cross-section of 1 sq. metre, when the temperature gradient is 1° C. per metre.

The figures thus obtained cover a temperature range of $t_1 - t_2$, which is about 10° C. As measurements at different temperatures showed that the thermal conductivity changes but little with the temperature (about 1 per cent. per 10° C.), the figures obtained also represent the thermal conductivity at a given temperature, viz. at the mean temperature of the range $t_1 - t_2$.

The thermal conductivities at convenient temperatures were computed by interpolation from the values thus found for the thermal conductivity at different temperatures (see Table IV).

These values show that the thermal conductivity is practically the same for all bitumens.

These values for the thermal conductivity expressed in kg.-cal./m./°C./h (this manner of recording is the most suitable for technical use) may be converted into g.-cal./cm./°C./sec. units by multiplication by the factor 0·00278.

M. Jacob [9] (see also [2] and [4]) found a thermal conductivity of 0·14 kg.-cal./m./°C./h between 0° C. and the softening point R. & B.; this value is thus in good agreement with our values.

TABLE IV.

Thermal Conductivity of Asphaltic Bitumens.

Bitumen.	Pen. at 25° C. IPT.–A. 18.	Soft. pt. R. & B. IPT.–A. 20.	Thermal conductivity in kg.-cal./m./° C./h.				
			0° C.	20° C.	40° C.	60° C.	70° C.
Venezuelan distilled bitumen . .	177	39½° C.	0·136	0·133	0·130	—	—
Ditto . . .	23	62½	0·141	0·137	0·133	0·129	0·125
Ditto . . .	7	96½	0·144	0·137	0·130	0·124	0·127
Mexican distilled bitumen . . .	22½	65	0·137	0·135	0·133	0·131	—
Ditto, blown . .	39	84½	0·141	0·139	0·138	0·136	0·134
Ditto, blown . .	25	86½	0·150	0·146	0·143	0·140	0·136
Bitumen from cracked residue . .	2	73	—	0·129	0·126	0·124	0·121
Light-coloured bitumen	25	53	0·120	0·117	0·115	—	—

SURFACE TENSION AND TOTAL SURFACE ENERGY.

The surface tension of various bitumens was measured by means of the apparatus developed by Du Nouy (in a hydrogen atmosphere), at such high temperatures that the bitumen was sufficiently liquid to permit the determinations.[10]

With this apparatus the force necessary to draw a metal ring of known diameter from the bitumen is determined.

The value obtained must be corrected for the peculiar shape of the liquid film which is formed when the ring is drawn up.

As a method which permits of reliable determinations of the surface

TABLE V.

Surface Tension and Total Surface Energy of Bitumens.

Bitumen.	Penetration at 25° C. IPT.–A. 18.	Soft. pt. R. & B. IPT.–A. 20.	Surface tension in dynes/cm.				Total surface energy ergs/sq. cm.
			150° C.	120° C.	100° C.	25° C. (obtained by extrapolation).	
Distilled Indian bitumen . . .	250	33° C.	26·9	28·8	30·0	34·4	51
Distilled Venezuelan bitumen . .	200	39° C.	26·0	27·7	28·8	33·0	50
Distilled Mexican bitumen . .	190	42° C.	25·5	—	28·7	33·5	51
Ditto . . .	50	58° C.	26·2	28·1	29·4	34·2	52
Blown Mexican bitumen . . .	190	—	24·8	—	28·1	33·0	50
Ditto . . .	34	85° C.	24·1	26·1	—	32·1	52

The values found by Dr. Nellensteyn[11] at higher temperatures (above 140° C.), determined by Jaeger's bubble pressure method, are in good agreement with our figures.

tension of bitumens at room temperature has not yet been developed, the surface tension at 25° C. had to be computed by extrapolation.

The total surface energy E_s was calculated from the following equation :

$$E_s = \sigma - T\frac{d\sigma}{dT}$$

E_s = total surface energy,
σ = surface tension,
T = absolute temperature.

Table V gives a summary of the surface tension at different temperatures and of the total surface energy of different grades of bitumen. The surface tension values obtained in these measurements are accurate to within about 0·5.

The difference between the values obtained by linear extrapolation and the true values will be very slight, as the value for the total surface energy would fall outside the limits of 50–70 ergs/sq. cm. (between which lie the total surface energies of all hydrocarbons), even in the event of a slight deviation from the linear relation between surface tension and temperature.

Permeability to Water Vapour.

The permeability to water vapour is an important factor in several applications of asphaltic bitumens, in particular as insulating material in the electric industry.

We have not made any measurements of this property. Taylor, Herrmann, and Kemp, however, have determined this property on various materials, including a bitumen sealing compound (presumably a blown asphaltic bitumen)[12]; see also.[4]

For determining the coefficient of diffusion of the water vapour within the material, Fick's diffusion law was used, which is expressed by the following equation :

$$N = \frac{DAt}{x}(p_1 - p_2),$$

where N = the amount of water that will diffuse in time t in the direction x through a cross-section with a surface area A, $p_1 - p_2$ being the difference in the vapour pressure of the water.

This law applies perfectly to materials which absorb practically no water (polystyrene). On the other hand, it cannot be expected that water-absorbing materials obey Fick's law.

In most cases in which water is absorbed, less water passes through the material than in the equilibrium condition. As the above determinations had been carried out under conditions approaching equilibrium, the rate of permeation was constant in the case of a definite thickness of the material and at definite vapour pressures. With water-absorbing materials, however, the rate of permeation, also under equilibrium conditions, generally depends on the values of the vapour pressures and the difference between these, and moreover on the thickness of the material. This is due to the fact that the rate of permeation is in general governed by the amount of water absorbed; the distribution in the material and the amount of this absorbed water are dependent on the values of the vapour pressures, the difference between these and the thickness of the material.

As stated by the authors, the values obtained in the above determinations, some of which are given in Table VI, may, as far as water-absorbing materials are concerned, be considered only as approximate constants; they are therefore only to be considered as exact under the conditions stated above.

TABLE VI.

Permeability to Water Vapour of Various Materials, including Asphaltic Bitumen.

Material.	Temp., °C.	Thickness of material, cm.	Water vapour pressure $p_1 - p_2$ in mm. Hg.*	Coefficient of diffusion D in $g \cdot h^{-1} \cdot cm.^{-1}$ mm. Hg^{-1}.
Paraffin wax	21·1	0·05	18·6—0·0	0·06 10^{-4}
Polyethylene tetrasulphide (thiokol)	21·1	0·08	18·0—0·0	0·22 ,,
Bitumen sealing compound	25·0	0·08	22·8—0·0	1·15 ,,
Plasticized cellulose acetate	25·0	0·002	22·8—0·0	1·18 ,,
Gutta-percha	25·0	0·03	22·8—0·0	1·48 ,,
Ebonite	25·0	0·05	22·8—0·0	1·51 ,,
Balata	25·0	0·04	22·8—0·0	1·80 ,,
Paragutta	25·0	0·05	22·8—0·0	1·89 ,,
Polystyrene	21·1	0·1	18·0—0·0	3·9 ,,
Moulded bakelite	25·0	0·05	22·8—0·0	4·7 ,,
Phenol fibre	25·0	0·08	22·8—0·0	5·0 ,,
Soft vulcanized rubber	25·0	0·04	22·8—0·0	7·3 ,,
Benzyl cellulose	23·9	0·07	22·8—0·0	10·6 ,,
Cellulose acetate	25·0	0·02	22·8—0·0	160·0 ,,

* As the above figures show, the relative vapour pressure on the one side is about 1.

The permeability to water vapour has been expressed in the table by the coefficient of diffusion D; this represents the amount of water vapour (in grams) which, at a vapour pressure difference of 1 mm. Hg, would diffuse in one hour through a layer of 1 cm. thickness having a surface area of 1 sq. cm., if Fick's law would hold.

E. Badum [12] also determined the permeability to water vapour of various substances. His figures are in good agreement with those of the authors mentioned before. For asphaltic bitumen he found a diffusion coefficient of

$$1{\cdot}4 \times 10^{-4}\ g \cdot h^{-1} \cdot cm.^{-1} \cdot mm.\ Hg^{-1}.$$

Amsterdam Laboratory of the *N.V. de Bataafsche Petroleum Maatschappij.*

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OBITUARY.

DONALD C. BARTON.

DR. DONALD C. BARTON, research geologist and geophysicist with the Humble Oil & Refining Company, died in Houston, Texas, 8th July, after a three weeks' illness.

Dr. Barton was known internationally for his work in the interpretation of the physiography of the Gulf Coast region, and for his numerous papers on the geology of salt domes. He was a leader in the use of geophysical methods and their application to petroleum exploration, having begun this study in the early 1920's. Later he used his geological and geophysical knowledge to determine and portray the broad geologic structure of the Gulf Coast region. Out of this study came his recognition of the Gulf Coast geosyncline, sometimes referred to as the Barton geosyncline. While most of Dr. Barton's working life was spent in commercial work, he was a persistent thinker, and found time to carry on an unusual amount of scientific research.

Dr. Barton was born in Stow, Massachusetts, in 1888, and was educated at Harvard University, receiving the degree of Doctor of Philosophy in 1914. He was instructor in geology at Washington University, leaving that position to do geologic work with the Empire Gas & Fuel Company until the World War. He served in France during the War. From 1919 to 1923 he was division geologist at Houston for the Amerada Petroleum Corporation, and was chief geologist for the Rycade Oil Corporation from 1923 to 1927. For the next seven years he worked as a consulting geologist, accepting the position with the Humble Company in 1934.

Dr. Barton was a Member of the Institute of Petroleum since 1926. He was also a member of the Société Géologique de France, the American Association of Petroleum Geologists, of which he was President in 1938–1939, the Geological Society of America, the American Institute of Mining and Metallurgical Engineers, the Society of Economic Geologists, and the American Geophysical Union.

L. T. B.